USAAVLABS TECHNICAL REPORT 71-17

A FULL-SCALE EXPERIMENTAL FEASIBILITY STUDY OF HELICOPTER ROTOR ISOLATION USING THE DYNAMIC ANTIRESONANT VIBRATION ISOLATOR

By

Robert Jones

June 1971

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

CONTRACT DAAJ02-68-C-0094
KAMAN AEROSPACE CORPORATION
BLOOMFIELD, CONNECTICUT

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1. ORIGINATING ACTIVITY *(Corporate author)* Kaman Aerospace Corporation Bloomfield, Connecticut	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

A FULL-SCALE EXPERIMENTAL FEASIBILITY STUDY OF HELICOPTER ROTOR ISOLATION USING THE DYNAMIC ANTIRESONANT VIBRATION ISOLATOR

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Final Report

5. AUTHOR(S) *(First name, middle initial, last name)*

Robert Jones

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
June 1971	143	10

8a. CONTRACT OR GRANT NO. DAAJ02-68-C-0094 b. PROJECT NO. Task 1F162204A14608 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) USAAVLABS Technical Report 71-17 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* Kaman Report R-892

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory Fort Eustis, Virginia

13. ABSTRACT

This report contains the results of a full-scale experimental feasibility study of rotor isolation employing the Dynamic Antiresonant Vibration Isolator (DAVI).

The full-scale experiments were performed on a UH-2 helicopter fuselage isolated from a simulated rotor and transmission. Tests were conducted for three directions of vibratory input at the hub on the nonisolated vehicle and then compared to results obtained for the isolated vehicles. Tests on the isolated helicopter were conducted for two-bladed,three-bladed, and four-bladed rotor configurations. These rotor configurations were simulated by proper tuning of the DAVI isolation system to the predominant excitation frequency of the rotor systems.

Results of this experimental study on a 6500-pound helicopter show that rotor isolation is feasible. Excellent reduction of vibration throughout the fuselage was obtained at the predominant excitation frequency (n-per-rev). This was accomplished with low static deflection, minimum weight penalty, and small relative vibratory deflections between the rotor and fuselage.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

UNCLASSIFIED
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Rotor isolation						
Helicopter isolation						
Isolation						
Vibration isolation						
Antiresonant isolation						

Prior research was conducted to assess the feasibility of helicopter rotor isolation using the Dynamic Antiresonant Vibration Isolator (DAVI). Rotor isolation was found to be feasible for "statistical" helicopters ranging from 2,000 pounds to 100,000 pounds.

The DAVI is a mechanically simple, three-directional passive device exhibiting high static stiffness while simultaneously offering an antiresonant frequency which may be tuned to be coincident with the predominate frequency of excitation - rotor blade passage frequency. The DAVI provides an antiresonance and consequently isolation simultaneously in the vertical, lateral, and longitudinal directions. Being passive, it requires no power supply.

This contract was initiated to experimentally demonstrate rotor isolation feasibility by full-scale ground vibration testing. For this program, a three-directional isolation system incorporating four DAVI's of a single size suitable for installation in either a 6,500- or a 10,000-pound vehicle was designed. Isolator parameters were not optimized for either gross weight or any one rotor configuration. Consequently, optimization for performance or minimum weight was not attempted. The test vehicle consisted of a stripped UH-2 ballasted to 6,500 pounds gross weight to simulate a UH-1 helicopter. The free-flight condition was simulated by suspending the test vehicle from the rotor hub by a bungee and, in turn, suspending the fuselage from the upper body (rotor and transmission) by the isolation system. Tests consisted of exciting the rotor hub with sufficient magnitude to induce responses in excess of $\pm$ .2g in the unisolated aircraft. Excitation frequency was varied to represent two-, three-, and four-bladed helicopters. Excellent isolation and displacement control were attained, confirming earlier predictions. Results were particularly good for the three- and four-bladed configurations. The two-bladed results were good considering the difficulty of affording isolation for this configuration. This difficulty stems from: (1) the predominant 2/rev and 1/rev frequencies' being very close at about 10 Hz and 5 Hz respectively, (2) the isolator natural frequency's being above 1/rev to preclude mechanical instability and (3) the predominant fuselage response modes' being close to the 1/rev. The close proximity of these frequencies makes isolation of the two-bladed configuration most difficult.

Task 1F162204A14608
Contract DAAJ02-68-C-0094
USAAVLABS Technical Report 71-17
June 1971

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Final Report

Kaman Report No. R-892

By

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This report contains the results of a full-scale experimental feasibility study of rotor isolation employing the Dynamic Antiresonant Vibration Isolator (DAVI).

The full-scale experiments were performed on a UH-2 helicopter fuselage isolated from a simulated rotor and transmission. Tests were conducted for three directions of vibratory input at the hub on the nonisolated vehicle and then compared to results obtained for the isolated vehicle. Tests on the isolated helicopter were conducted for two-bladed, three-bladed, and four-bladed rotor configurations. These rotor configurations were simulated by proper tuning of the DAVI isolation system to the predominant excitation frequency of the rotor systems.

Results of this experimental study on a 6500-pound helicopter show that rotor isolation is feasible. Excellent reduction of vibration throughout the fuselage was obtained at the predominant excitation frequency (n-per-rev). This was accomplished with low static deflection, minimum weight penalty, and small relative vibratory deflections between the rotor and fuselage.

FOREWORD

This research program for the full-scale experimental feasibility study was performed by Kaman Aerospace Corporation, Division of Kaman Corporation, Bloomfield, Connecticut, under Contract DAAJ02-68-C-0094, Task 1F162204A14608, for the Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia.

The program was conducted by the Aeromechanics Research Group of the Research Section at Kaman. Mr. E. P. Schuett was Project Engineer. The program was conducted under the technical direction of Mr. J. McGarvey, Contracting Officer's Representative, USAAVLABS.

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LIST OF SYMBOLS

a	Distance from the center of the isolated platform to the spring, ft
b	Distance from the center of the isolated platform to the isolated pivot, ft
E_α	Pitch effectivity
E_x	Longitudinal effectivity
E_z	Vertical effectivity
E_y	Lateral effectivity
E_θ	Roll effectivity
I	Rotational inertia of isolated platform, slug-ft^2
I_D	DAVI inertia bar, slug-ft^2
I_{F_x}	Roll inertia of lower body, slug-ft^2
I_{F_y}	Pitch inertia of lower body, slug-ft^2
I_{F_z}	Yaw inertia of lower body, slug-ft^2
I_{R_x}	Roll inertia of upper body, slug-ft^2
I_{R_y}	Pitch inertia of upper body, slug-ft^2
I_{R_z}	Yaw inertia of upper body, slug-ft^2

LIST OF SYMBOLS (Continued)

I_{s_x}	Roll inertia of aircraft, slug-ft^2
I_{s_y}	Pitch inertia of aircraft, slug-ft^2
I_{s_z}	Yaw inertia of aircraft, slug-ft^2
K_D	Spring rate of DAVI, lb/ft
M	Mass of isolated platform, slugs
M_A	Effective mass of DAVI inertia bar at antiresonance, slugs
M_D	Mass of DAVI inertia bar, slugs
M_F	Lower body mass, slugs
M_R	Upper body mass, slugs
M'_R	Effective mass of DAVI inertia bar at resonance, slugs
M_s	Mass of aircraft, slugs
r	Distance between pivots on DAVI inertia bar, ft
R	Distance of DAVI inertia bar cg from isolated pivot, ft
T	Kinetic energy, ft-lb
V	Potential energy, ft-lb

LIST OF SYMBOLS (Continued)

z	Vertical displacement of isolated platform, ft
z_D	Vertical displacement of DAVI inertia bar cg, ft
z_o	Vertical displacement of input, ft
θ	Rotational displacement of isolated platform, rad
θ_D	Rotational displacement of DAVI inertia bar, rad
θ_o	Rotational displacement of input, rad
ρ	Radius of gyration of the DAVI inertia bar, ft
ω	Frequency of the input, rad/sec
ω_A	Antiresonant frequency of the DAVI, rad/sec
ω_{A_T}	Antiresonant frequency of the DAVI for translation, rad/sec
ω_{A_R}	Antiresonant frequency of the DAVI for rotation, rad/sec

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INTRODUCTION

Through company- and government-sponsored research, great advancements have been made in rotary-wing analysis and design. Even so, major vibration problems still exist in present-day helicopters. With the coming of faster helicopters, heavier helicopters, and compounds and composite aircraft, these vibration problems will in all probability increase. These vibration problems not only have increased the development time of rotary-wing aircraft and are a source of pilot fatigue, but in all probability are the cause of lower rotary-wing availability due to higher maintenance and lower reliability.

The major source of these vibration problems is the rotor-induced shears and moments. The nature of these shears and moments is such as to produce an input at the hub at a frequency that is an integral multiple of the number of blades in the rotor system. The predominant frequency of excitation is the "nth" harmonic of an n-bladed rotor; i.e., for a two-bladed helicopter, the predominant frequency is two-per-rev of a two-bladed rotor. These rotor-induced shears and moments produce high-level, low-frequency vibration in the fuselage. In present-day helicopters, this predominant frequency range is between approximately 8.5 and 30 Hertz.

Several approaches can be taken to reduce helicopter vibration. One approach is the reduction of the vertical and in-plane shears, utilizing higher harmonic pitch control (References 1 and 2). Another approach to reduce rotary-wing vibration levels is rotor isolation or the isolation of the fuselage from the rotor-induced shears and moments. The latter approach is the subject of this report.

Rotor isolation is not new. Conventional passive isolation is used in some present-day helicopters to isolate the in-plane shears. However, these soft isolation systems cannot be used for vertical isolation because of the large static deflection and the excessive deflection encountered during maneuvers. Research in rotor isolation has continued for many years. In the earlier published research studies (References 3, 4, and 5), active systems were studied and recommended for vertical isolation.

More recently, due to the increased knowledge in the state of the art of both active and passive vibration systems, USAAVLABS, Fort Eustis, Virginia, sponsored research to determine the analytical feasibility of rotor isolation. The results of this research are reported in References 6 and 7. In

Reference 6, passive rotor isolation was shown to be analytically feasible utilizing the Kaman Dynamic Antiresonant Vibration Isolator (DAVI).

The DAVI is a passive isolator that provides a high degree of isolation at low frequency with very low static deflection. At the antiresonant frequency of the DAVI, inertia forces cancel spring forces, producing a nearly zero transmissibility across the DAVI, which is independent of the isolated mass. The DAVI has been shown to be feasible through analysis and laboratory testing (References 8 and 9) and through flight testing of a DAVI-isolated platform (Reference 10).

This study attempts to determine the experimental feasibility of rotor isolation on a full-scale helicopter. This program was conducted on a Kaman UH-2 helicopter in which the fuselage was isolated from the rotor by a DAVI isolation system. The rotor and transmission were simulated by an upper body with proper weight and inertial characteristics.

DISCUSSION

Rotor isolation using the Kaman Dynamic Antiresonant Vibration Isolator (DAVI) has been determined to be analytically feasible for helicopters with gross weights from 2000 pounds to 100,000 pounds. The study reported in Reference 6 showed that excellent isolation was obtained with a very low weight penalty and with small static and vibratory deflections in the isolation system.

In order to confirm these analytical results, a full-scale experimental rotor isolation program was conducted on a UH-2 helicopter at a gross weight of 6500 pounds modified to incorporate a four-point three-dimensional DAVI isolation system. The structure of the fuselage was not modified; however, the rotor and transmission were simulated by appropriate weight and inertial characteristics. The aircraft was suspended on a soft bungee system to simulate a free-free system.

The nonisolated vehicle was tested for vertical, longitudinal, and lateral vibratory force inputs at the hub. These force inputs were of a magnitude to produce the vibratory levels that could be expected in flight. With the same directions of inputs and the same magnitude of vibratory force level, tests were conducted on a three-dimensional DAVI-isolated helicopter for two-, three-, and four-bladed rotor configurations. The antiresonance of the DAVI was tuned to the predominant excitation frequency (n-per-rev) of the rotor to simulate the three rotor configurations tested.

Testing an actual helicopter structure with the proper magnitude of forces to obtain the fuselage response that could be expected in flight gives a good evaluation of a rotor isolation system.

From this type of full-scale testing, the rotor isolation system can be evaluated to determine the reduction of vibration levels and the amount of relative deflection between the upper and lower bodies expected in flight. The system can also be evaluated to determine future design changes required to make it more efficient.

Table I shows the average responses of the nonisolated and isolated vehicle. The average responses were obtained for three levels of vibration on the nonisolated helicopter; less than $\pm.05$ g, between $\pm.05$g and $\pm.10$g, and greater than $\pm.10$g. It is seen from this table that for all levels of vibration, a reduction of vibration occurred for the isolated

TABLE I. RANGE OF RESPONSES AT THE PREDOMINANT ROTOR EXCITATION N/REV

Response Range ($\pm g$)	4-Bladed Rotor N*	4-Bladed Rotor Avg Response ($\pm g$) Non-Iso	4-Bladed Rotor Avg Response ($\pm g$) Iso	4-Bladed Rotor Tϕ	3-Bladed Rotor N*	3-Bladed Rotor Avg Response ($\pm g$) Non-Iso	3-Bladed Rotor Avg Response ($\pm g$) Iso	3-Bladed Rotor Tϕ	2-Bladed Rotor N*	2-Bladed Rotor Avg Response ($\pm g$) Non-Iso	2-Bladed Rotor Avg Response ($\pm g$) Iso	2-Bladed Rotor Tϕ
Vertical Excitation												
<.05	0	-	-	-	0	-	-	-	3	.026	.025	.95
.05-.10	3	.0773	.016	.21	3	.086	.019	.22	5	.0596	.0404	.68
>.10	6	.253	.022	.09	6	.335	.040	.12	1	.152	.064	.42
Longitudinal Excitation												
<.05	3	.0327	.02	.61	0	-	-	-	3	.039	.023	.60
.05-.10	0	-	-	-	2	.068	.0385	.57	2	.061	.030	.50
>.10	6	.1948	.0418	.21	7	.4889	.0993	.20	4	.262	.137	.52
Lateral Excitation												
<.05	1	.029	.010	.34	3	.02	.021	1.05	4	.026	.019	.731
.05-.10	7	.0601	.085	.58	4	.0803	.0507	.63	3	.0827	.068	.82
>.10	1	.161	.064	.40	2	.1865	.1335	.71	2	.1165	.026	.22
All Directions of Excitation												
>.10	13	.2191	.0344	.16	15	.3870	.0801	.21	7	.2047	.0949	.46

*N - Number of occurrences of nonisolated responses in each response range listed in column one.

ϕT - Transmissibility; ratio isolated/nonisolated response.

cases. The isolation system was the most effective at the highest response range for which the lowest transmissibility was obtained. In comparing the average results of the high response range of the nonisolated helicopter to the isolated helicopter for all directions of excitation, it is seen that for the three- and four-bladed rotor configuration, essentially 80 percent isolation was obtained. For the two-bladed rotor configuration, over 50 percent isolation was obtained.

Table II shows the actual g levels obtained at the predominant excitation frequency of the rotor configurations tested (for all locations of the transducers). It is seen from this table that for almost every location and direction of the transducers, a reduction of vibration resulted. For the few locations and directions at which a small increase in vibration was encountered, the amplitude of the response was low. It is also seen from this table that the three-dimensional DAVI isolation system was more effective for the vertical and longitudinal directions of excitation than for the lateral direction of excitation. However, the amplitude of the response for the nonisolated helicopter was low for the lateral direction of excitation. But even with this low response, a reduction in the vibration amplitude was obtained.

It is further seen from Table II that the DAVI isolation system was more effective for the four- and three-bladed rotor configurations than for the two-bladed configuration in that a greater percentage of vibration reduction was obtained on the four- and three-bladed rotor configurations than on the two-bladed configuration. However, the amplitudes of vibration were all of the same approximate magnitude for the three isolated rotor configurations. This resulted in a vibration level of much less than ± 0.1 g throughout the fuselage structure for most conditions.

For this test program, a three-dimensional DAVI isolation system incorporating 4 DAVI's of a single size suitable for installation in either a 6500-lb or a 10,000-lb vehicle was designed. Isolator parameters were not optimized for either gross weight or any one rotor configuration. The DAVI's were designed to have a tuning range (range of antiresonance) from 9 to 22 Hertz. Spherical rod-end bearings were used for the inertia bar pivots. Laboratory and flight test experiments reported in References 8 and 10 show that rod-end bearings give less isolation than flexural pivots. This is because rod-end bearings, unlike flexural pivots, are not friction-free; they introduce damping and consequently afford less isolation. Nevertheless, rod-end bearings were selected because:

TABLE II. VIBRATION LEVELS OF THE PREDOMINANT ROTOR EXCITATION

Pickup Location		Acceleration ($\pm g$)					
		4-Bladed Rotor		3-Bladed Rotor		2-Bladed Rotor	
Sta	Direction	Non-Iso	Iso	Non-Iso	Iso	Non-Iso	Iso
Vertical Excitation							
400	Vert	.244	.020	.742	.088	.050	.060
	Long.	.191	.005	.223	.038	.024	.017
	Lat	.086	.005	.616	.072	.031	.024
170	Vert	.200	.029	.128	.013	.093	.065
	Long.	.051	.010	.166	.010	.050	.017
	Lat	.237	.025	.134	.019	.023	.033
50	Vert	.543	.043	.090	.028	.152	.064
	Long.	.103	.010	.076	.010	.055	.025
	Lat	.095	.033	.092	.020	.050	.035
Longitudinal Excitation							
400	Vert	.283	.067	1.253	.148	.450	.261
	Long.	.236	.058	.734	.157	.230	.136
	Lat	.011	.014	.443	.137	.044	.034
170	Vert	.040	.027	.067	.044	.051	.025
	Long.	.101	.029	.282	.065	.133	.053
	Lat	.047	.019	.069	.033	.036	.017
50	Vert	.265	.027	.301	.065	.235	.097
	Long.	.119	.039	.249	.060	.070	.035
	Lat	.165	.031	.160	.063	.038	.018

TABLE II - Continued

Lateral Excitation							
		Acceleration ($\pm g$)					
		4-Bladed Rotor		3-Bladed Rotor		2-Bladed Rotor	
Pickup Location		Non-Iso	Iso	Non-Iso	Iso	Non-Iso	Iso
Sta	Direction						
	Vert	.052	.025	.268	.206	.079	.108
400	Long.	.055	.040	.093	.083	.017	.017
	Lat	.052	.038	.105	.061	.131	.008
	Vert	.052	.028	.027	.035	.034	.016
170	Long.	.070	.020	.019	.019	.018	.026
	Lat	.029	.010	.054	.023	.086	.050
	Vert	.079	.074	.099	.078	.083	.047
50	Long.	.061	.020	.014	.009	.035	.017
	Lat	.161	.064	.075	.019	.102	.044

(1) readily available flexural pivots were neither large enough to accommodate the relatively heavy masses to be tested nor capable of providing relative motion about mutually perpendicular coincident axes (hooks joint type motion without which weight and envelope size are compromised), and

(2) it was known that at these heavier masses the rod-end bearings would be working nearer to their design capacities, thereby performing better than earlier tests suggest.

Therefore, by designing the DAVI isolation system to a specific vehicle size and rotor configuration and reducing the damping in the system by a different pivot design, even greater reduction in vibration levels on the fuselage could be obtained.

Table III shows the relative deflection obtained in the isolation system for the three rotor configurations tested. It is seen that the relative deflection obtained was small. The largest relative deflections for the vertical and longitudinal directions of excitation were ± 0.0212 inch and ± 0.0320 inch respectively. Assuming that the ± 0.0320 inch relative deflection is due only to rotation of the upper body, then the rotation of the upper body is only ± 0.07 degree. Also assuming that the translation at the coupling is the sum of the two motions or ± 0.0532 inch, then for a relatively short engine drive system of 10.0 inches, the rotation in the coupling is only ± 0.32 degree. These rotations, which should be similar to those expected in flight, are well within the minimum design limits of ± 0.75 degree of present-day couplings.

It is seen from these results that a substantial reduction in vibration levels of the fuselage was obtained with small relative deflections. These results show the feasibility of the DAVI for rotor isolation.

TABLE III. VERTICAL RELATIVE DEFLECTION IN THE DAVI ISOLATION SYSTEM FOR THE PREDOMINANT EXCITATION FREQUENCY

DAVI Location	Relative Deflection (±in.)		
	4-Bladed Rotor	3-Bladed Rotor	2-Bladed Rotor
Vertical Excitation			
Left Fwd	.0068	.0121	.0171
Right Fwd	.0083	.0162	.0094
Right Aft	.0006	.0106	.0212
Left Aft	.0077	.0156	.0040
Longitudinal Excitation			
Left Fwd	.0072	.0156	.0125
Right Fwd	.0042	.0131	.0320
Right Aft	.0006	.0078	.0264
Left Aft	.0040	.0210	.0026
Lateral Excitation			
Left Fwd	.0150	.0120	.0081
Right Fwd	.0110	.0076	.0069
Right Aft	.0084	.0046	.0036
Left Aft	.0114	.0056	.0034

ANALYSIS

As part of this rotor isolation study, an analysis was conducted to determine the proper design parameters for a three-dimensional DAVI isolation system and a two-dimensional DAVI with conventional isolation in the third direction. The analysis was conducted on the twelve-degree-of-freedom digital program developed under USAAVLABS Contract DA 44-177-AMC-420(T) and reported in Reference 1. This analysis was conducted for a 6500-pound vehicle and a 10,000-pound vehicle. Table IV summarizes the physical parameters of the vehicles studied. The analysis was based upon a four-point mounting system, the location of which is shown in Figure 1. The goal of this study was to achieve low static deflection with minimum weight and size, and also to determine the parameters of a single DAVI configuration suitable for use in the isolation system of either a 6500-pound or a 10,000-pound helicopter. As shown in Table IV, the DAVI configuration must have a tuning range from 9 to 22 Hertz for the aircraft configurations of interest.

Figure 2 presents a variation of DAVI inertia bar weights with static deflection for a four-bladed 10,000-pound helicopter, and for a two-bladed 6500-pound helicopter. For the 10,000-pound helicopter, the weight variation was plotted for five values of the nondimensional design ratio R/r. This figure shows the weight variation obtainable due to the flexibility of the DAVI design parameters of static deflection (δ_{ST}) and the ratio of the inertia rod center of gravity distance to pivot distance (R/r). This figure also shows that to obtain a reasonable weight and size of the DAVI with low static deflection, the R/r values should be between -4 and -8. Although an R/r value of -10 has a lower weight, the envelope or size of the DAVI is becoming large. As for the 10,000-pound helicopter, the results obtained for the 6500-pound helicopter show a large weight variation as a function of the DAVI design ratio R/r. This figure also shows that to obtain a reasonable weight and size of the DAVI with low static deflection, the R/r value should be at least -8.

Figure 3 presents a variation of the nondimensional design ratio R/r with antiresonant frequency for DAVI's having a static deflection of 0.1 inch and 0.075 inch. It is seen from this figure that a single DAVI can be designed to have a sufficient range in antiresonant frequencies for the simulated three-, four-, and five-bladed 10,000-pound vehicle to be tested.

TABLE IV. SUMMARY OF PHYSICAL PARAMETERS OF HELICOPTER CONFIGURATIONS ANALYZED

No. of Blades	N/Rev (Hertz)	Gr Wt (lb)	m_S (slugs)	m_R (slugs)	m_F (slugs)	I_{S_X} (slug-ft^2)	I_{S_Y} (slug-ft^2)	I_{S_X} (slug-ft^2)	I_{R_X} (slug-ft^2)	I_{R_Y} (slug-ft^2)	I_{R_Z} (slug-ft^2)
2	9.9	6,500	201.86	40.37	161.49	1478.8	5,534.8	5,196.8	37.6	38.0	1.37
3	14.8	6,500	201.86	40.37	161.49	1478.8	5,534.8	5,196.8	37.6	38.0	1.37
4	19.8	6,500	201.86	40.37	161.49	1478.8	5,534.8	5,196.8	37.6	38.0	1.37
3	13.1	10,000	310.55	62.11	248.44	3500.0	13,100.0	12,300.0	89.0	90.0	3.24
4	17.5	10,000	310.55	62.11	248.44	3500.0	13,100.0	12,300.0	89.0	90.0	3.24
5	21.8	10,000	310.55	62.11	248.44	3500.0	13,100.0	12,300.0	89.0	90.0	3.24

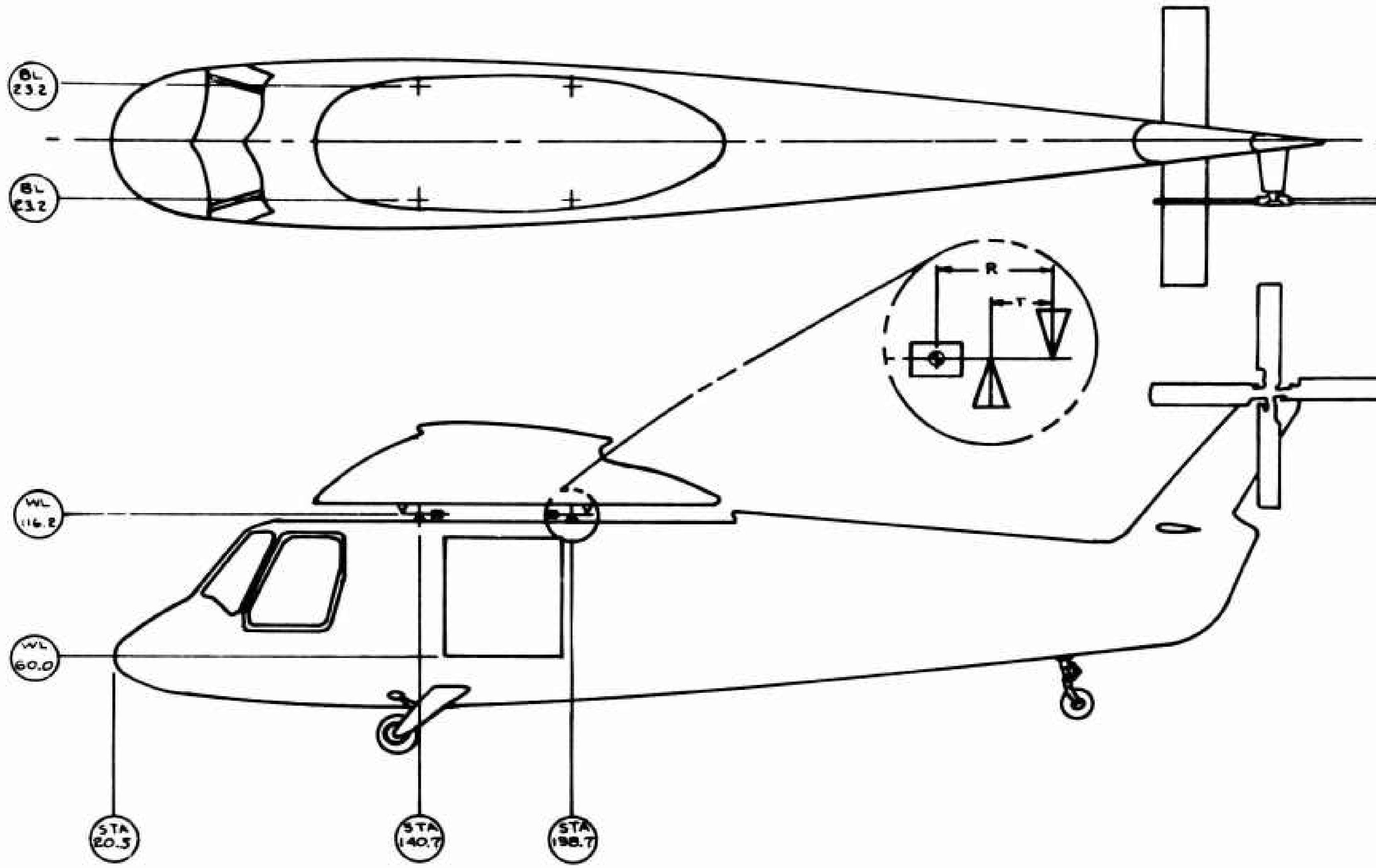


Figure 1. Schematic of a Four-Point Mounting System.

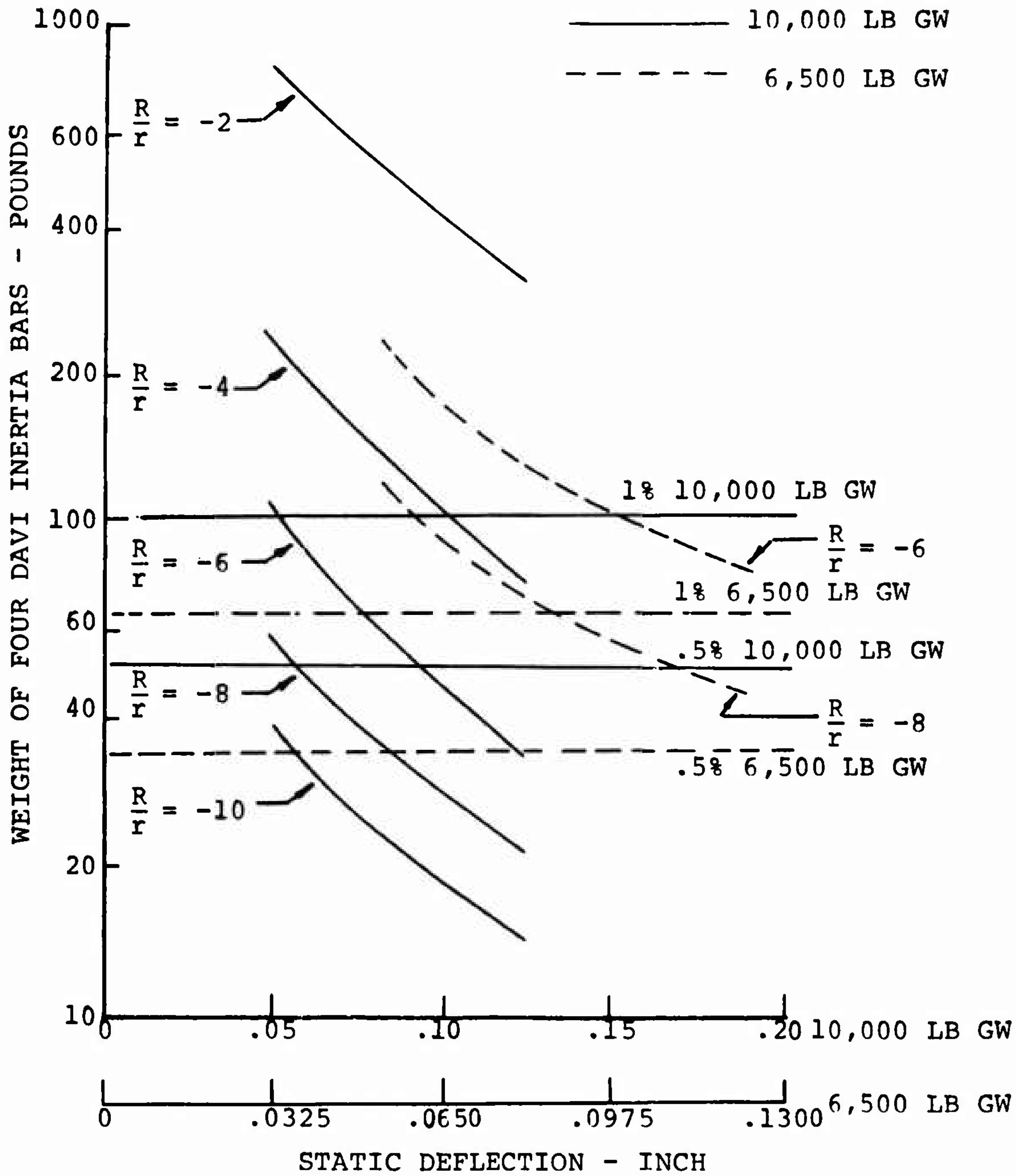


Figure 2. Variation of DAVI Inertia Bar Weight With Static Deflection.

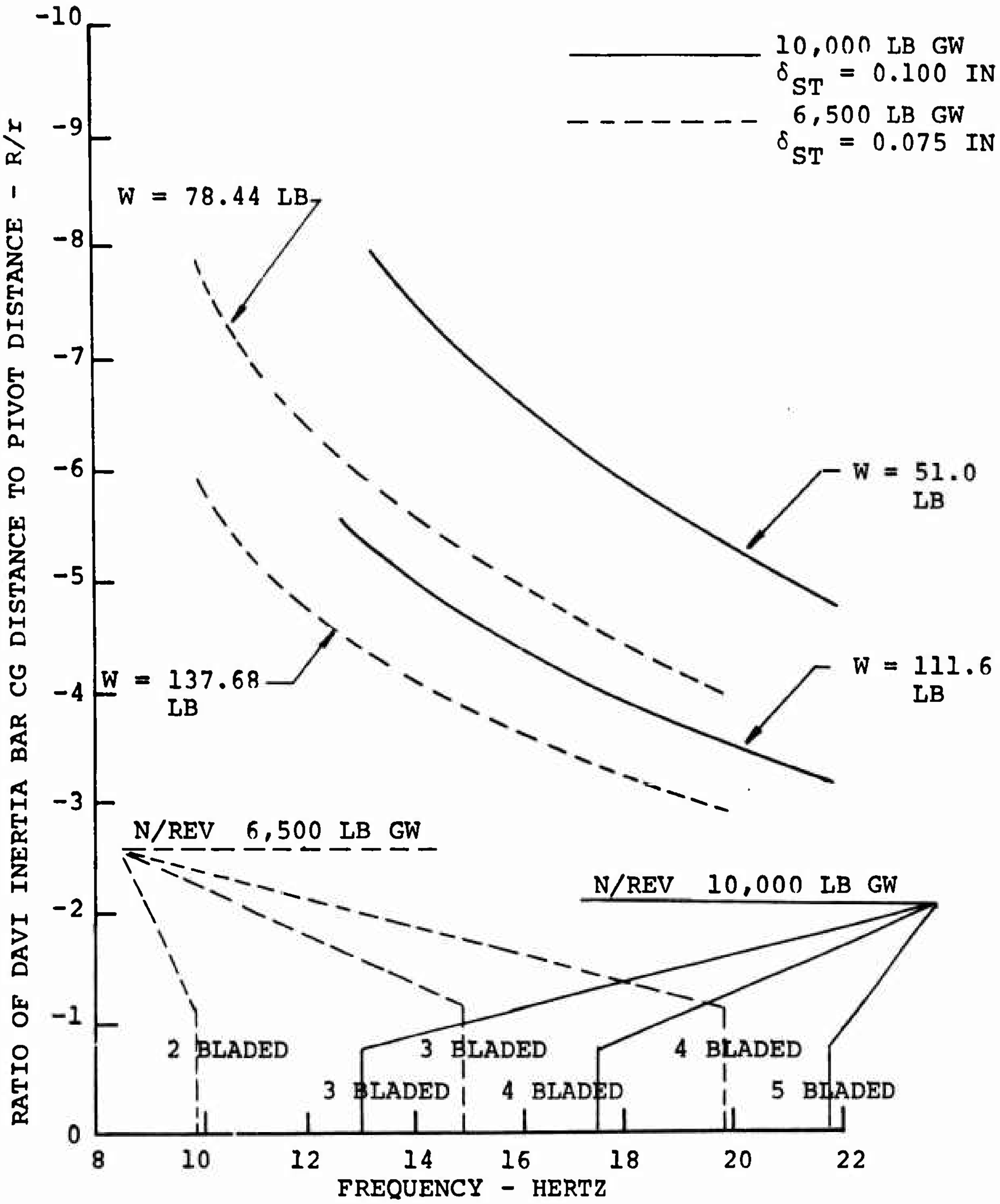


Figure 3. Variation of Antiresonant Frequency With the Ratio of DAVI Inertia Bar CG Distance to Pivot Distance.

It is seen also from this figure that a single DAVI can be designed to have a sufficient range in antiresonant frequencies for the simulated two-, three-, and four-bladed 6500-pound vehicles to be tested.

Figures 2 and 3 definitely show that a DAVI isolation design for a two-bladed 6500-pound configuration is the most difficult. This design difficulty is due to the low n-per-rev frequency, and the close proximity of the one-per-rev, the natural frequencies of the system, and the n-per-rev. Therefore, to obtain good isolation, a heavier DAVI with larger R/r and low damping is required as compared to the other rotor and weight configurations studied and tested.

Further parametric studies were then made to determine if one DAVI with reasonable weight and size could be designed for the range of anti-frequencies and gross weights to be tested. Figure 4 shows the results of this parametric study. This figure shows the variation of the nondimensional design ratio R/r with antiresonant frequency for a DAVI having a static deflection of 0.075 inch for a 6500-pound helicopter and a static deflection of 0.115 inch for a 10,000-pound helicopter. It is seen from this figure that a DAVI with a constant spring rate and inertia bar weight and R/r from -8 to -3.5 could be designed to have the range of antiresonant frequencies required for the experimental program.

Table V gives the design parameters necessary for a four-point DAVI isolation system for a 6500-pound and 10,000-pound helicopter.

TABLE V. INDIVIDUAL DAVI DESIGN PARAMETERS

No. of Blades	Helicopter Weight (lb)	Antiresonant Frequency (Hertz)	Spring Rate (lb/in.)	Static Deflection (lb)	Individual Inertia Bar Weight (lb)	R/r
2	6,500	9.9	17333.0	.075	19.61	-8.0
3	6,500	14.8	17333.0	.075	19.61	-5.3
4	6,500	19.8	17333.0	.075	19.61	-3.9
3	10,000	13.1	17333.0	.115	19.61	-6.0
4	10,000	17.5	17333.0	.115	19.61	-4.5
5	10,000	21.8	17333.0	.115	19.61	-3.5

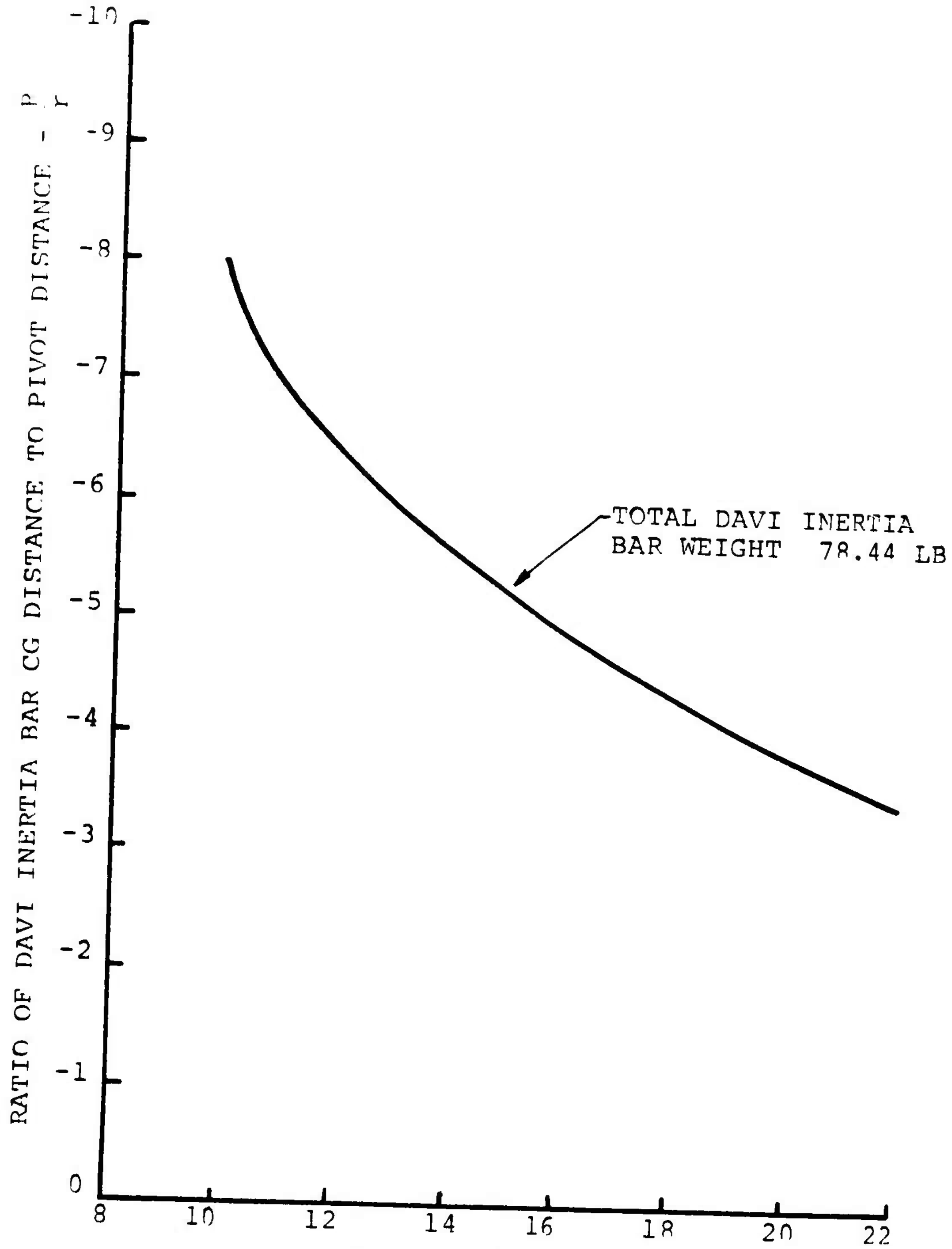


Figure 4. Variation of Antiresonant Frequency of the DAVI With the Ratio of DAVI Inertia Bar CG Distance to Pivot Distance for a 6500-Pound and 10,000-Pound Helicopter.

Three-dimensional DAVI configurations and two-dimensional DAVI configurations were analyzed.

Table VI shows the results obtained for the three-dimensional DAVI analysis.

TABLE VI. EFFECTIVITY AT N/REV FOR 3D-DAVI ISOLATION

No. of Blades	Gross Weight (lb)	N/Rev (Hertz)	E_{ϕ}	E_X	E_Z	E_Y	E_{θ}
2	6,500	9.9	694	815	305	212	226
3	6,500	14.8	79,043	139,891	39,334	34,123	31,656
4	6,500	19.8	111,488	182,199	58,720	46,959	43,645
3	10,000	13.1	553	754.5	199.1	551.3	461.5
4	10,000	17.5	57,533	97,607	23,292	62,860	45,968
5	10,000	21.8	131,834	241	54,278	150,810	105,852

It is seen from this table that excellent effectivity at the N/rev for all configurations was obtained. Effectivity is defined as the ratio of the response of the rigid system over the response of the isolated system at the same point. Therefore, the greater the effectivity, the better the isolation becomes.

Table VII compares the effectivity of the three-dimensional DAVI analysis with the two-dimensional DAVI analysis. In the two-dimensional DAVI analysis, DAVI isolation is in the vertical and lateral directions with conventional isolation in the longitudinal directions. In this table, only the effectivities for pitching and longitudinal motions are compared, since the other effectivities were of the same order of magnitude.

TABLE VII. COMPARATIVE EFFECTIVITY AT N/REV FOR 3D-DAVI AND 2D-DAVI ISOLATION						
No. of Blades	Gross Weight (lb)	N/Rev (Hertz)	E_α		E_x	
			2D-DAVI	3D-DAVI	2D-DAVI	3D-DAVI
2	6,500	9.9	16	694	6	816
4	10,000	17.5	36	57,533	13	97,607

The three-dimensional DAVI requires two inertia bars and therefore is heavier. However, because of the better isolation obtained in the analysis, and because excellent results were obtained in a flight test program as reported in Reference 10, a three-dimensional DAVI design was selected.

DESIGN

DAVI

A four-point three-dimensional DAVI isolation system was designed for a 6500-pound and a 10,000-pound helicopter. The DAVI units were designed for a 10,000-pound helicopter to a 3.0 g load factor (30,000 pounds of thrust) and -0.5 g load factor (-5000 pounds of thrust). Since the DAVI isolation system must also react torque, the system was designed to react ultimate torque.

The spring rate requirement, as given in Table V, was 17,333 lb/in. The springs were designed to have this spring rate in the vertical and in-plane directions. Many spring sizes were analyzed for the load conditions. Variation of the installation included the number of springs varying from two to eight, the coil and spring wire diameters, and space requirements. A configuration of four springs per DAVI was selected. The spring design is shown in Figure 5.

Figure 6 shows a three-view drawing of the DAVI and Figure 7 shows the DAVI model use in the tests. This three-dimensional DAVI has two inertia bars. The unidirectional inertia bar couples with motion along the vertical axis of the preloaded vertical springs and utilizes rod end bearings as the hinge for the rotor or input pivot. The fuselage or isolated pivot of the unidirectional inertia bar is a spherical bearing. This fuselage or isolated pivot is located between the cg of the unidirectional inertia bar and the rotor as input pivot. Therefore, the unidirectional inertia bar has a negative R/r. For the motions of this unidirectional inertia bar, the weight of the two-dimensional inertia bar adds to the isolated weight or fuselage.

The two-dimensional inertia bar couples with the in-plane motion of the spring and utilizes spherical bearings for both the fuselage or isolated and rotor or input pivots. The rotor or input pivot of the two-dimensional inertia bar and the fuselage or isolated pivot of the unidirectional inertia bar make up a common pivot. The fuselage or isolated pivot of the two-dimensional inertia bar is located between the cg of the inertia bar and the rotor or input pivot, and therefore the two-dimensional inertia bar has a negative R/r. For motions of the two-dimensional inertia bar, the weight of the unidirectional bar adds to the rotor weight.

The fuselage or isolated pivot of the unidirectional bar is on the vertical elastic axis of the spring system, and the isolated pivot of the two-dimensional inertia bar is on the

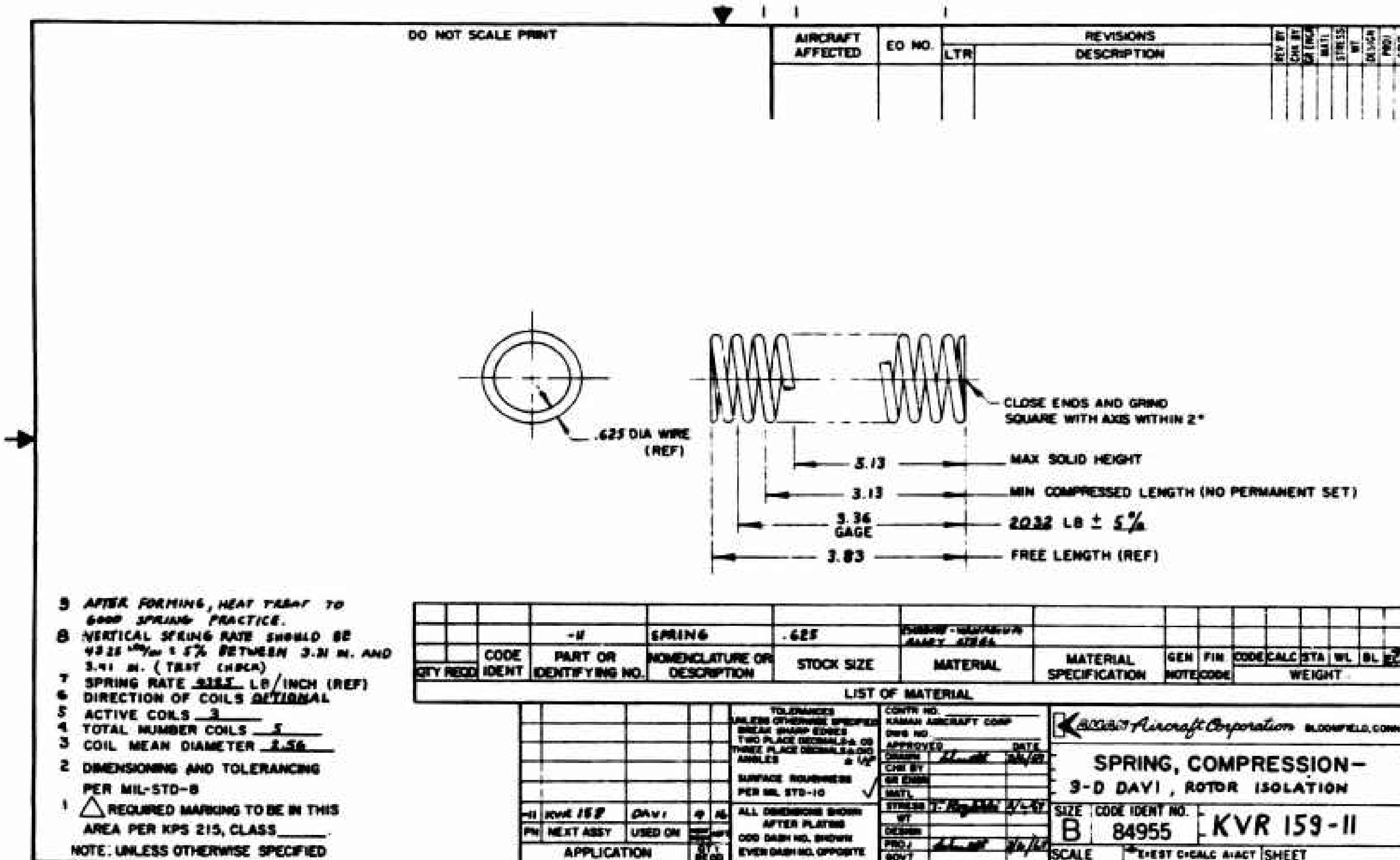


Figure 5. Three-Dimensional DAVI Spring Design.

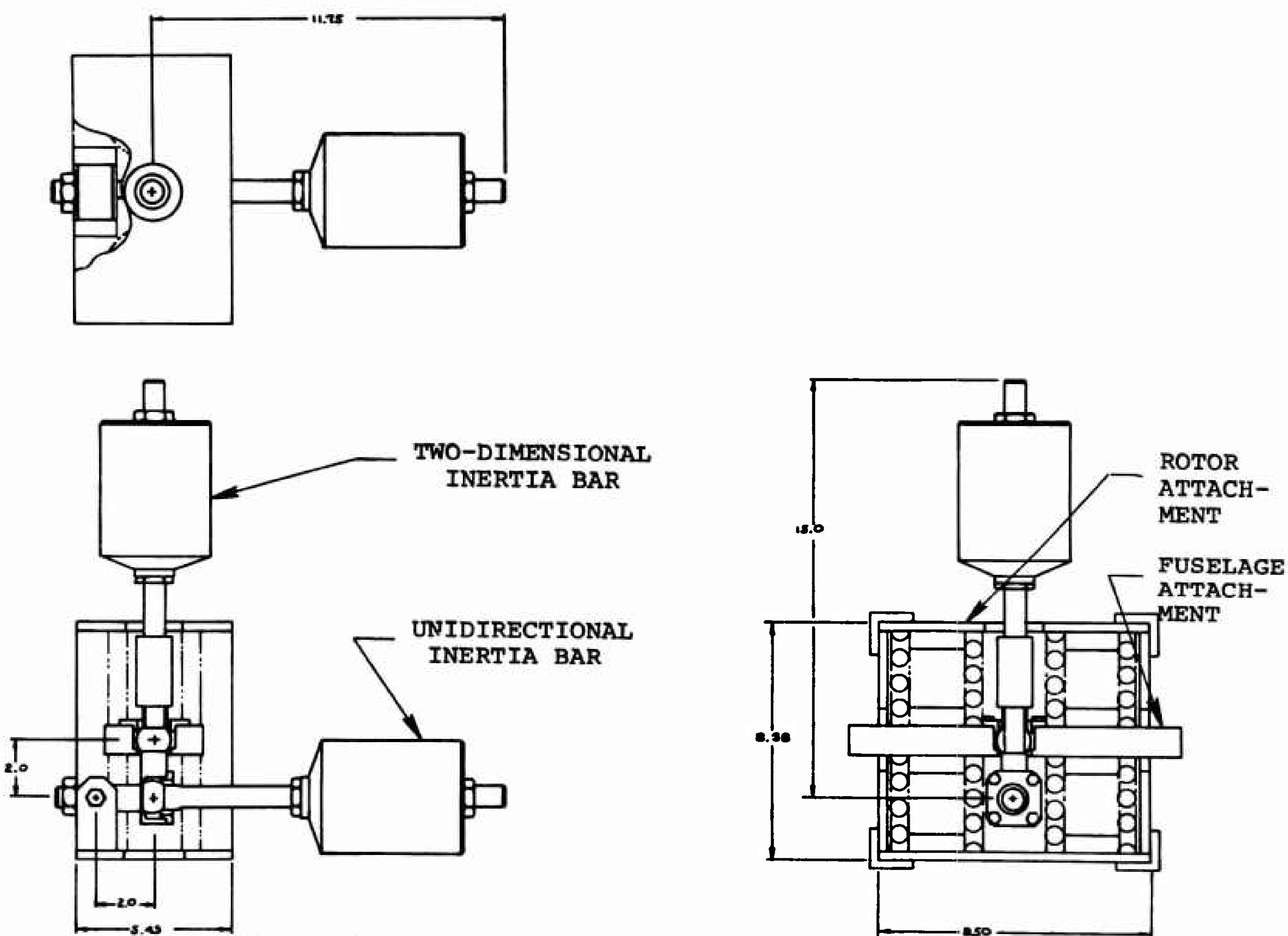


Figure 6. Three-View of the Three-Dimensional DAVI.

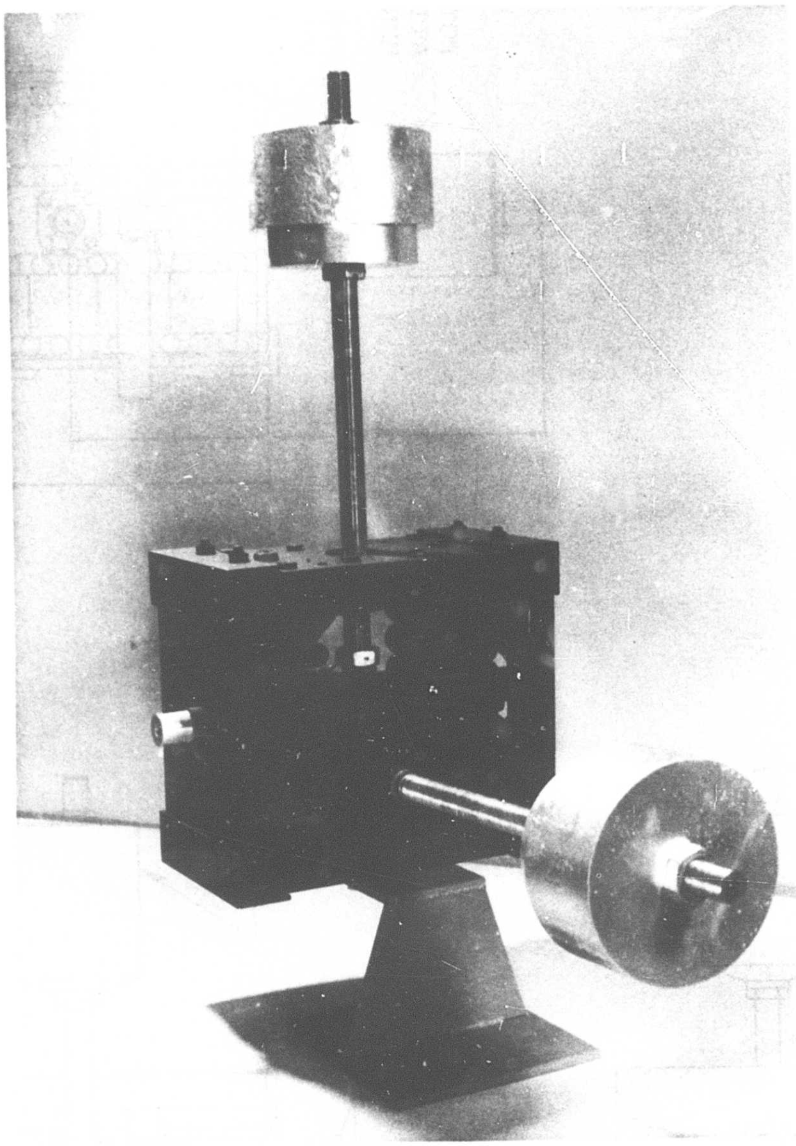


Figure 7. Full-Scale Three-Dimensional Model.

in-plane elastic axis of the spring system.

Table VIII shows the physical parameters of the individual three-dimensional DAVI.

TABLE VIII. PHYSICAL PARAMETERS OF THE THREE-DIMENSIONAL DAVI

Heli-copter (lb)	Spring Rate (lb/in.)		Pre-load (lb)	Total Vert Def Req (in.)	Total Vert Def Avail. (in.)	Pivot Distance r(in.)		Angular Deflection of Unidi-rectional Inertia Bar (deg)
	Vert	Lat				Vert	In-Plane	
6500	17300	17300	6000	.263	.405	2.0	2.0	7.5
10,000	17300	17300	6000	.405	.405	2.0	2.0	11.5

Upon fabrication of the four three-dimensional DAVI's, a load versus deflection test was conducted to determine the actual spring of each DAVI. Table IX gives these results.

TABLE IX. MEASURED SPRING RATE OF EACH DAVI

DAVI	Spring Rate - (lb/in.)	
	Vertical	In-Plane
1	15565	18127
2	15748	17000
3	16000	17157
4	15810	17649

It is seen from the above results that the spring rates of the individual three-dimensional DAVI's are not equal. However, in the vertical direction, there is less than a 1.4-percent variation from an average value of 15,780 pounds per inch; in the in-plane direction, there is less than a 3.7-percent variation from an average value of 17,483 pounds per inch.

It is also seen from Table IX that the actual average vertical spring rate (15,780 pounds per inch) fell below the design goal of 17,333 pounds per inch, whereas the in-plane spring rate was within 1.0 percent of the design goal. Vertical load versus deflection tests were conducted on individual springs, and the design value of the spring rate was achieved. Therefore, the discrepancy is apparently due to structural deflection within the fabricated DAVI.

This 9.0-percent reduction in vertical spring rate will not substantially affect the expected results. There will be a slight increase in the static deflection. Also, the fact that the vertical and in-plane spring rates are not equal does not affect the results, since the unidirectional inertia bar of the three-dimensional DAVI couples with the vertical spring and is tuned independently from the two-dimensional inertia which couples with the in-plane spring.

The three-dimensional DAVI was tuned on a specially constructed test fixture, shown in Figures 8 and 9. An electromagnetic shaker was connected to the input side of the DAVI and was used for the excitation. The output side of the DAVI was connected to a 1000-pound isolated weight, which was suspended from the ceiling by four straps. Two velocity pickups were attached to the input and output sides of the DAVI. The output of these pickups was fed to a vibration meter, and the results were manually recorded. The movable weight on the DAVI was manually adjusted to various positions, and the antiresonance was obtained. This procedure was used for both vertical and in-plane tuning. Figure 10 shows the variation in antiresonant frequency with position of the movable inertia bar weight.

It is seen from these results that one DAVI inertia bar weight of 17.5 pounds can be used for the unidirectional inertia bar. Depending upon the antiresonant frequency desired, either 17.5 pounds or 14.0 pounds must be used on the two-dimensional inertia bar.

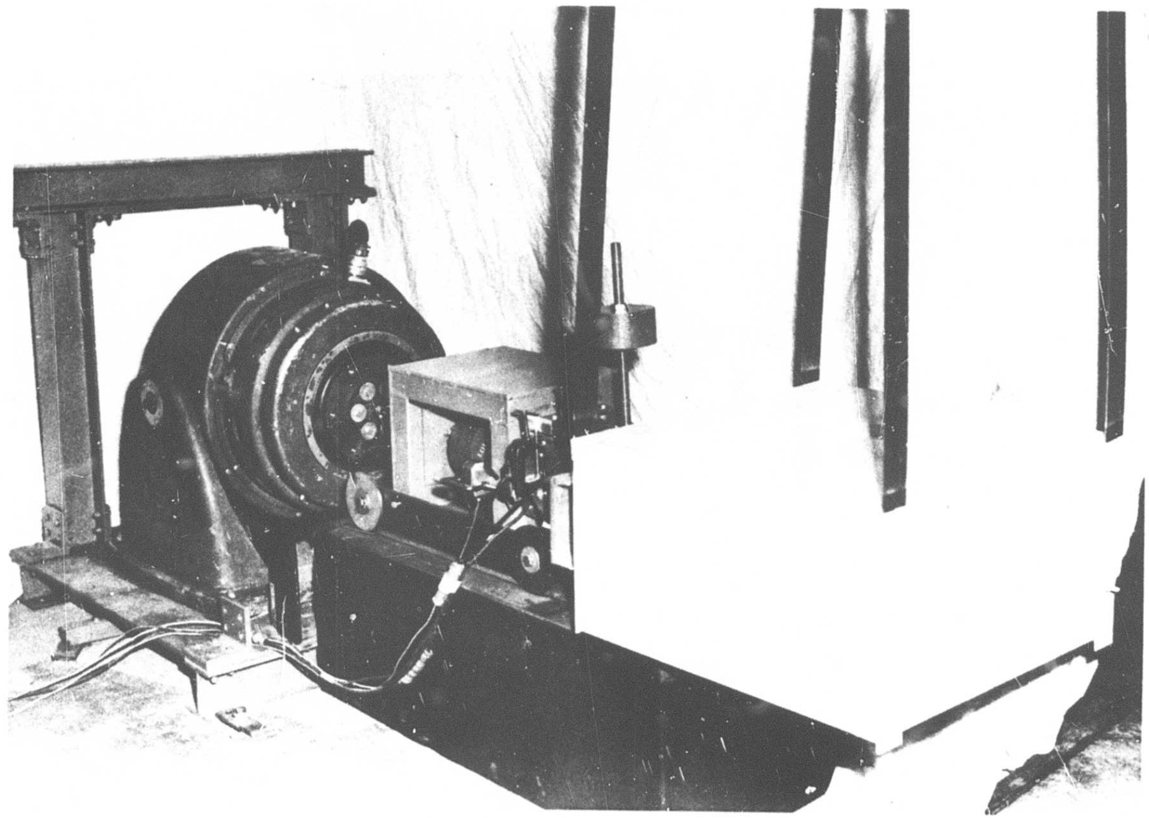


Figure 8. Overall View of the Tuning Rig.

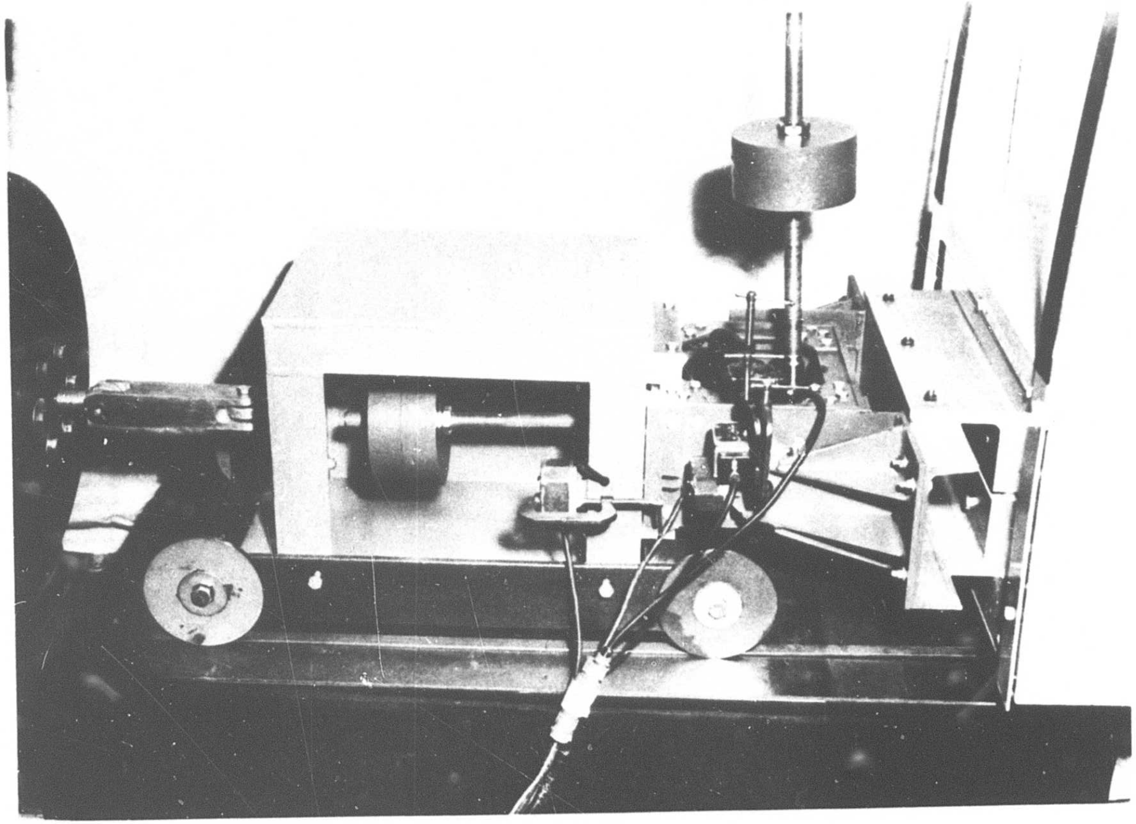
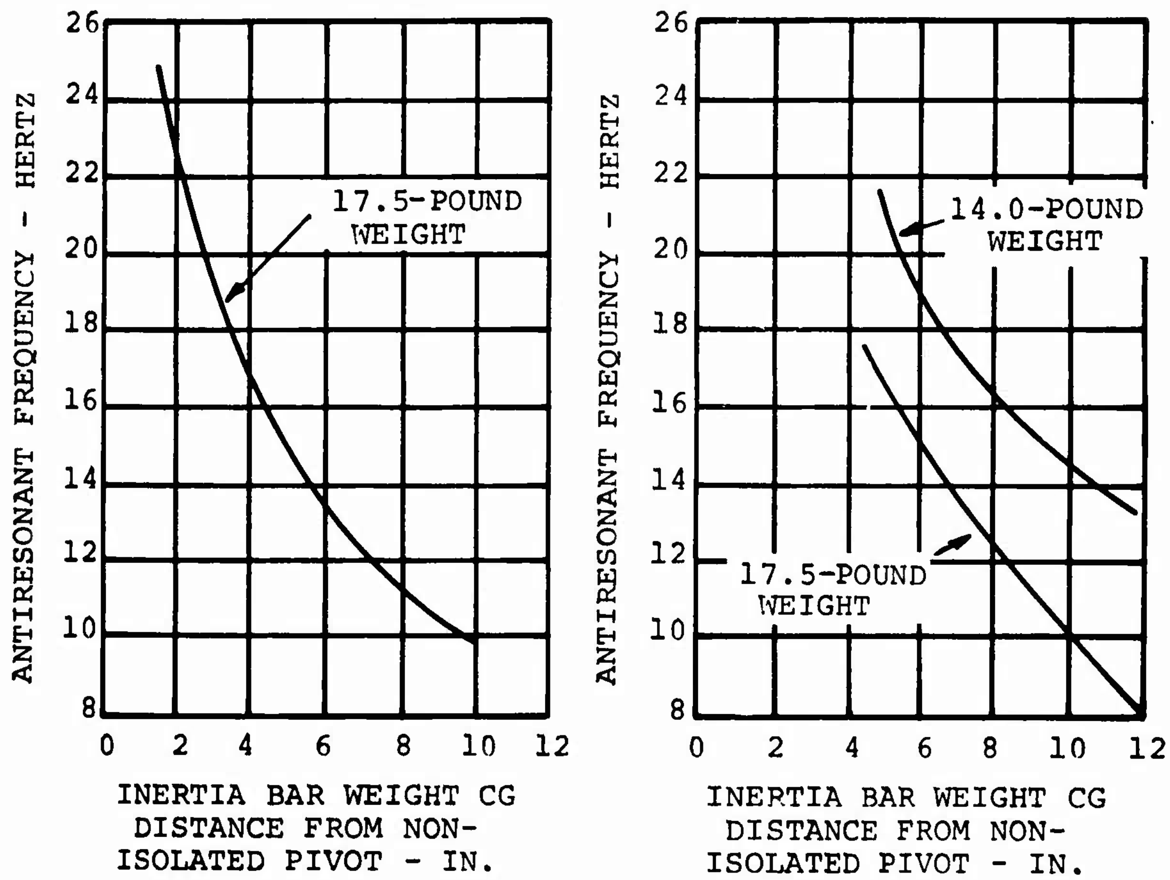


Figure 9. Tuning DAVI in Vertical Direction.



(a) Vertical

(b) In-Plane

Figure 10. Variation in Antiresonant Frequency With Position of Inertia Bar Weight.

AIRCRAFT

Fuselage

This full-scale experimental feasibility program was conducted on the UH-2B helicopter BuNo 147978. This helicopter was prepared for this program by removing all dynamic components; that is, main rotor, tail rotor, transmission, engine, drive systems, and all components above the roof. The stripped fuselage was then weighed and ballasted, including a dummy engine, to the parameters given in Table X , for a 6500-pound vehicle. The fuselage was ballasted to weigh 5200 pounds and have a cg located at station 169.74, water line 93.5, and butt line 0.0.

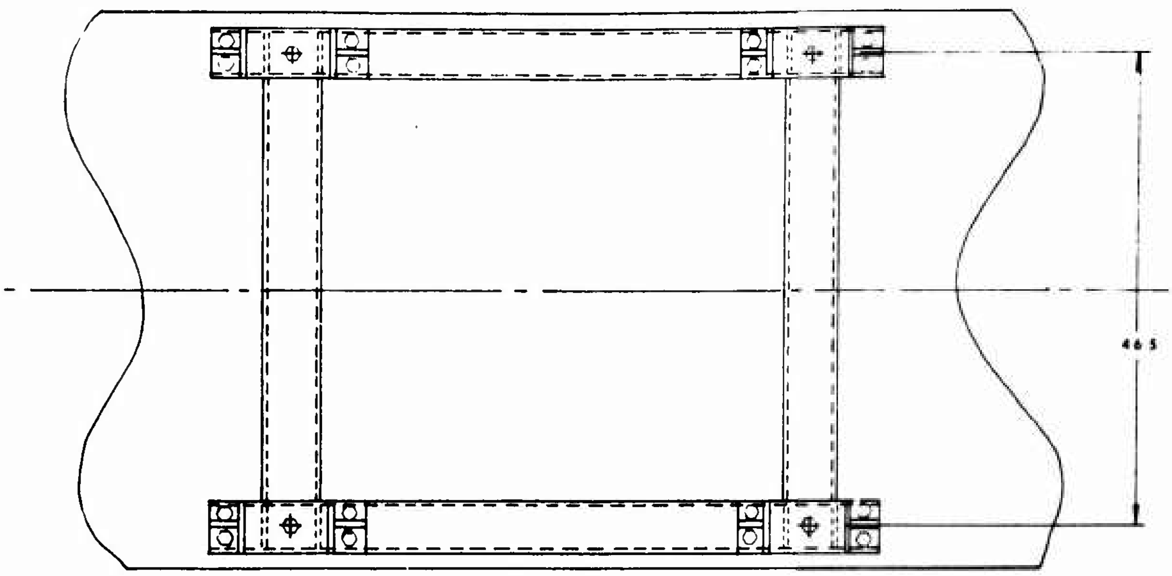
TABLE X. FUSELAGE BALLAST

Parameter	Unit	Magnitude
M_F	slugs	161.49
I_{FX}	slug-ft^2	419.30
I_{FY}	slug-ft^2	4475.00
I_{FZ}	slug-ft^2	5195.00

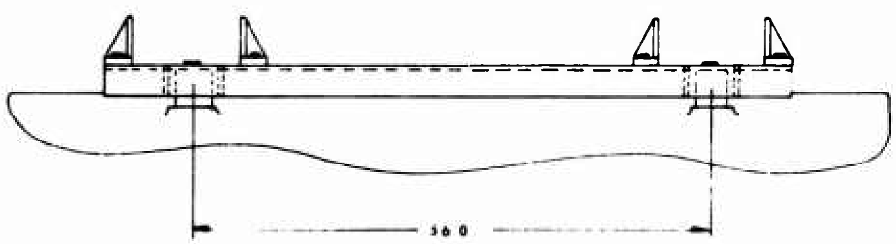
The fuselage structure was not modified other than the attachment of a platform to the transmission mounting points to support the three-dimensional DAVI's. This modification to the fuselage is shown in Figure 11.

Rotor and Transmission

The upper body of the test vehicle was a simulation of the rotor and transmission weight and inertia of a 6500-pound helicopter. Figure 12 shows a plan and profile view of the simulated rotor and transmission. Included as part of the upper body was the electromagnetic shaker used for the excitation. The two reasons for including the shaker in the upper body were that the shaker weighed 760 pounds and was a major part of the weight of the upper body and it was not necessary to construct a large test structure to react the forces. The upper body was ballasted to weigh 1300 pounds and to have a cg located at station 169.79, water line 161.0, and butt line 0.0. The upper body was ballasted to the parameters given in Table XI.

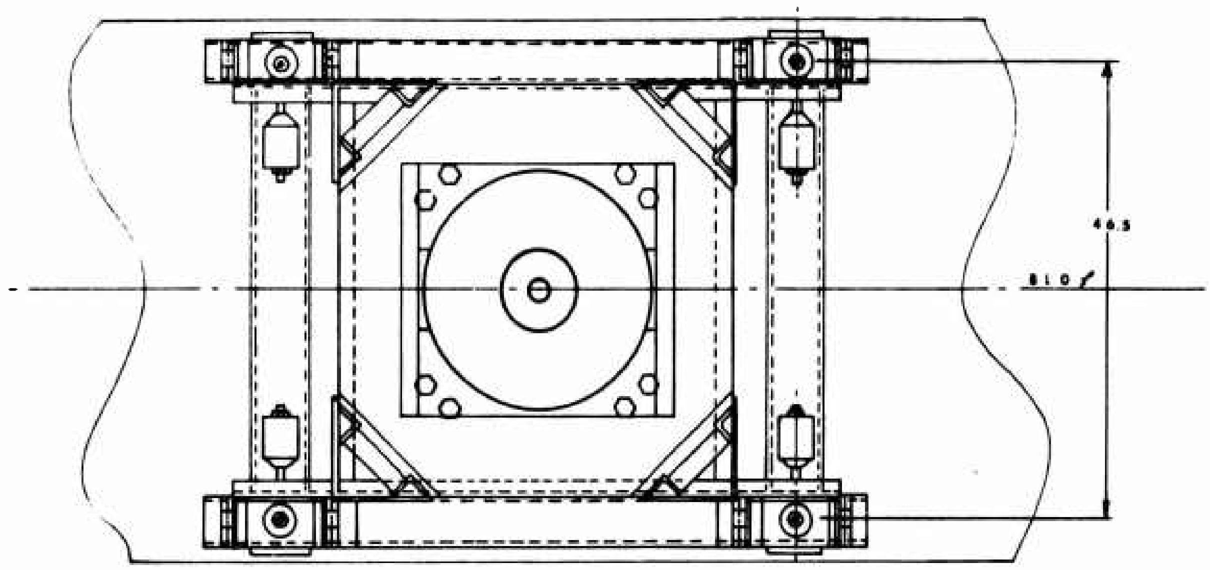


PLAN VIEW

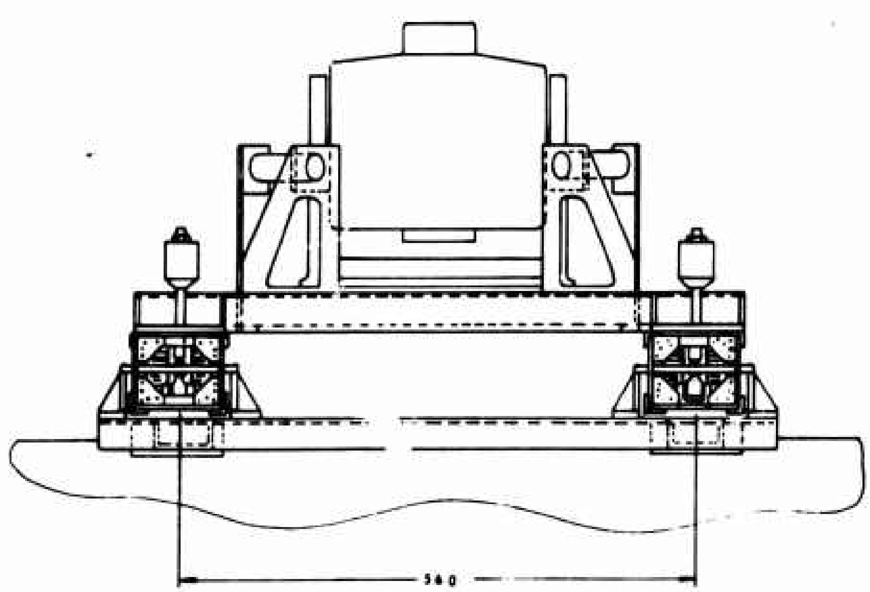


PROFILE VIEW

Figure 11. Three-Dimensional DAVI Attachment Platform.



PLAN VIEW



PROFILE VIEW

Figure 12. Simulated Rotor and Transmission.

TABLE XI. UPPER BODY BALLAST		
Parameter	Unit	Magnitude
M_R	slugs	40.37
I_{RX}	slug-ft^2	37.60
I_{RY}	slug-ft^2	38.03
I_{RZ}	slug-ft^2	1.37

Because of the weight of the shaker and the fact that the shaker must be rotated to obtain the proper direction of excitation, a simple design was incorporated in the upper body to float the 760-pound shaker on a cushion of air for in-plane rotation. This design allowed one man to rotate the shaker 90 degrees with no major disassembly required.

The fuselage was suspended from the simulated rotor and transmission by the three-dimensional DAVI isolation system, as seen in Figure 13. The complete test vehicle of 6500 pounds with a cg located at station 169.74, water line 107.0, and butt line 0.0 had the physical parameters shown in Table XII.

TABLE XII. COMPLETE VEHICLE BALLAST		
Parameter	Unit	Magnitude
M_S	slugs	201.86
I_{SX}	slug-ft^2	1479.00
I_{SY}	slug-ft^2	5535.00
I_{SZ}	slug-ft^2	5197.00

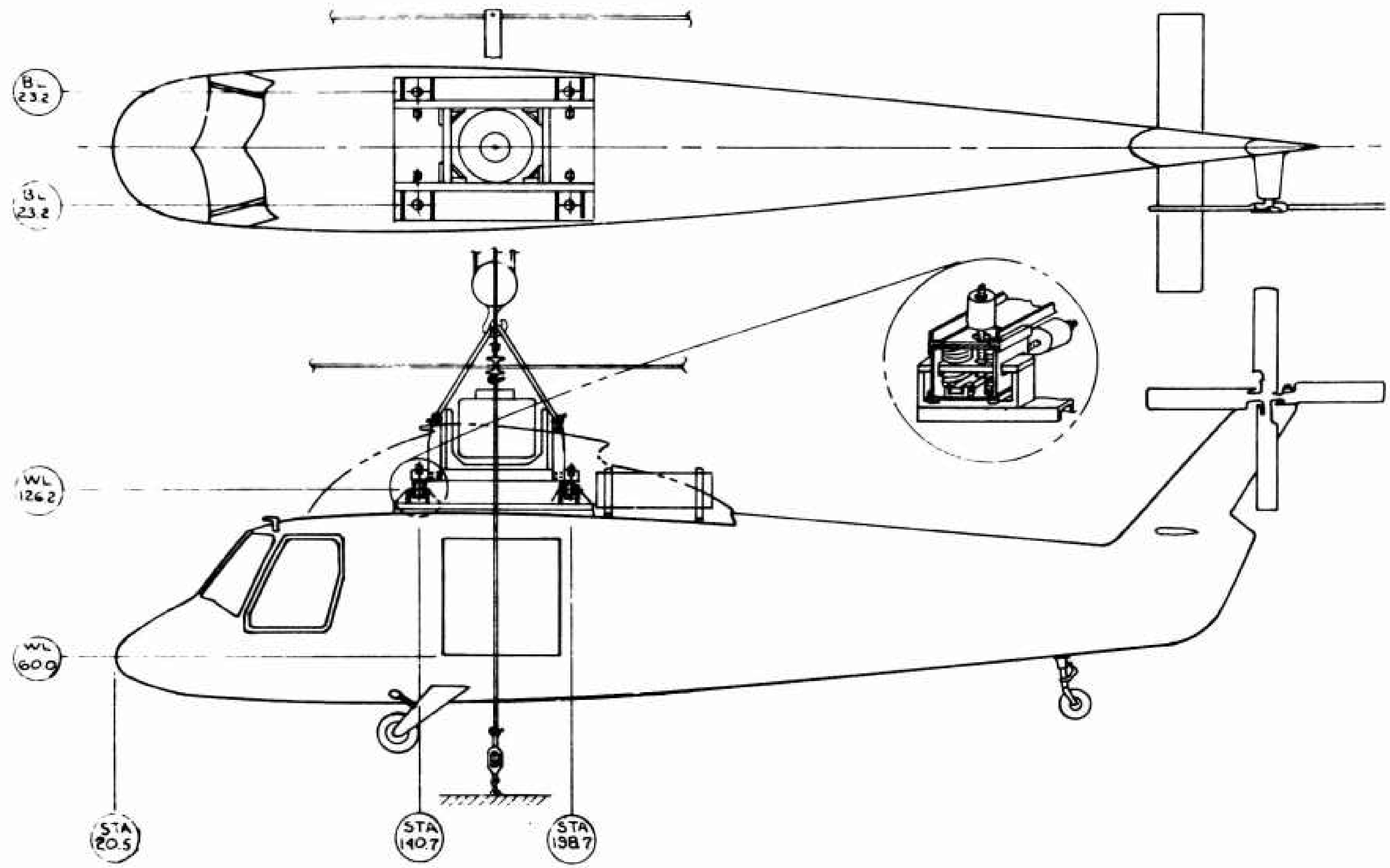


Figure 13. Simulated Rotor and Transmission Installed on Fuselage.

Reaction and Suspension System

The Kaman static test bay was used as the facility to conduct the full-scale experimental tests for rotor isolation. To simulate free-flight conditions, the simulated rotor and transmission was suspended from a 10-ton hoist by a soft bungee cord system. The natural frequencies were low as compared to the excitation frequencies of interest, and therefore the DAVI-isolated aircraft simulated free flight. Figure 14 is a schematic of the suspension system.

Since the electromagnetic shaker is part of the upper body weight, a system was designed to react all of the shaker excitation forces through tension in standard straps. This system is shown schematically in Figure 14. The straps run from load reaction beams on the static test frame to smaller reaction beams to which the shaker armature attaches. The reaction straps are tensioned by commercial turnbuckles, and the straps are never allowed to be in compression.

The weight of the small reaction beams is relieved by cable suspension from the frame overhead structure. For vertical excitation, the shaker armature is connected to the vertical reaction beam; for lateral excitation, the shaker is pivoted about its lateral axis and connected to the lateral reaction beam; for fore and aft excitation, the shaker is rotated 90 degrees using the air suspension system and is connected to the fore and aft reaction beam.

Figure 15 shows the test vehicle in the static test bay area.

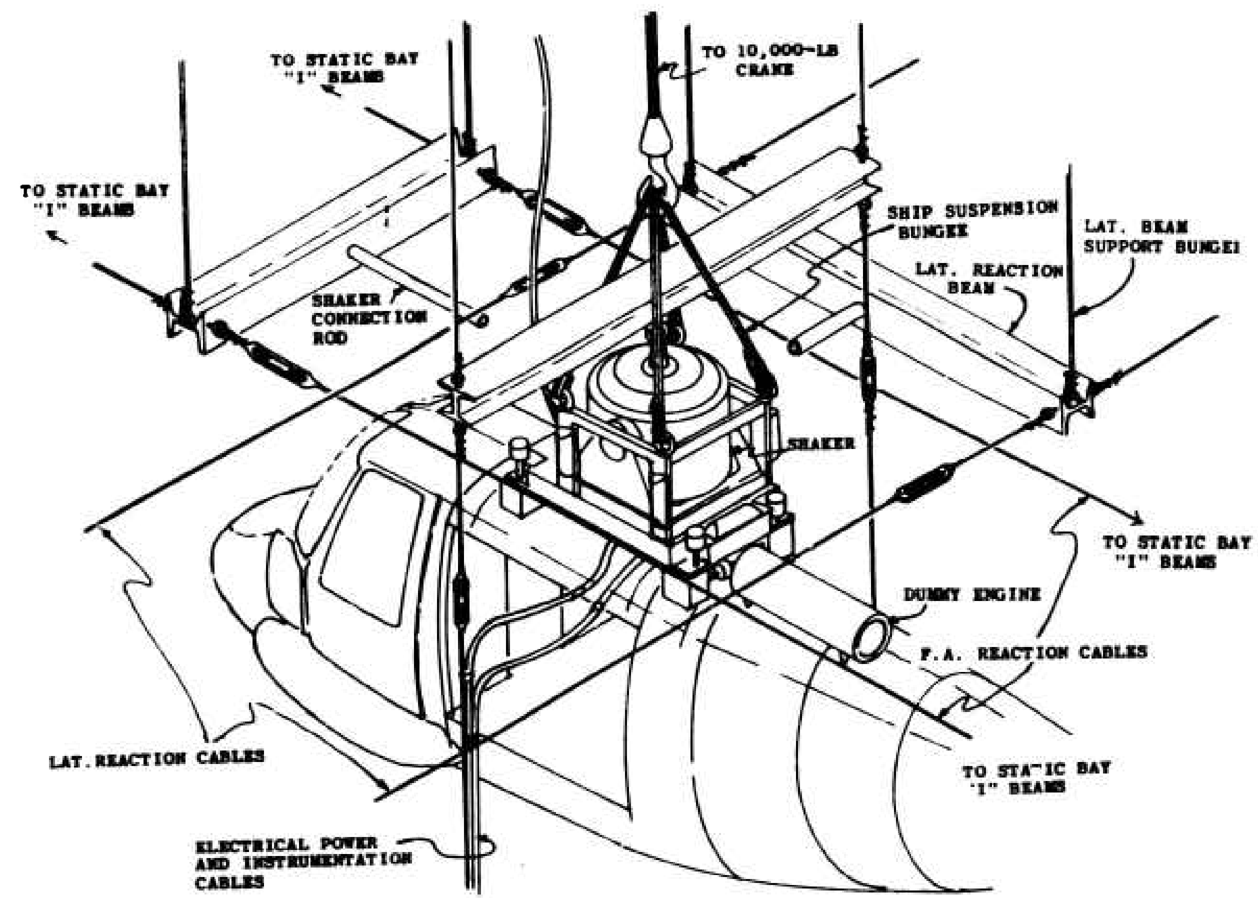


Figure 14. Schematic of the Suspension and Reaction Systems.

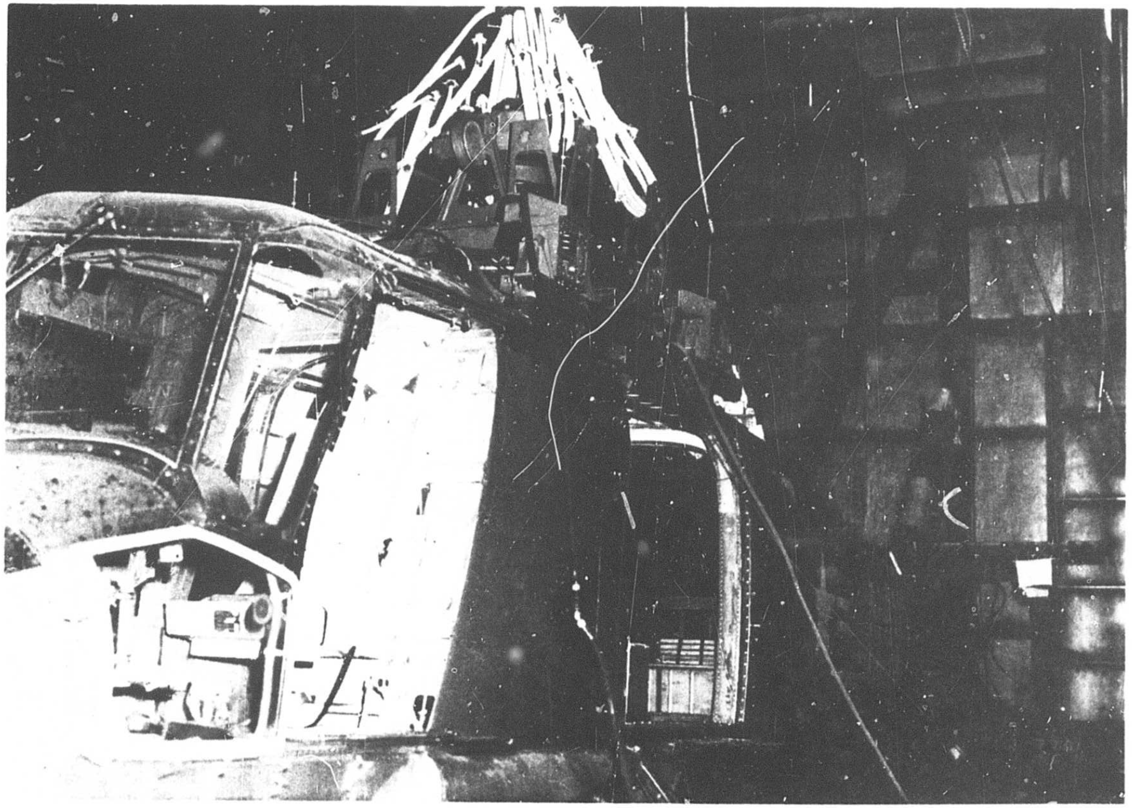


Figure 15. Test Vehicle in the Static Test Bay.

TEST

INSTRUMENTATION

The test vehicle was instrumented with ten accelerometers, three of which were located at approximately the center of gravity of the helicopter to pick up the vertical, lateral, and longitudinal accelerations. Three accelerometers were located at station 50 to pick up the vertical, lateral, and longitudinal accelerations. Three accelerations were located at station 400 to pick up the vertical, lateral, and longitudinal accelerations. One accelerometer was located at approximately the hub waterline and station to record the upper body acceleration in the direction of excitation. Figure 16 shows the location of the accelerometers.

Twelve linear potentiometers were located across the three-dimensional DAVI mounts. Three potentiometers were used at each mount to measure relative deflection between the upper body (rotor and transmission) and the fuselage in the vertical, lateral, and longitudinal directions. A load cell was installed between the shaker armature and the reaction beam to measure the force output of the electromagnetic shaker, which had a maximum capability of $\pm$750 pounds.

The output signals of the accelerometers, linear potentiometers, and load cell were recorded on two oscillographs. A cathode ray oscilloscope was used to monitor the force level, nose, cg, and tail accelerations. The oscillator frequency was monitored and manually recorded to insure the accuracy of the excitation frequency of the electromagnetic shaker.

TEST PROCEDURE

Table XIII lists the twelve basic tests conducted on the full-scale three-dimensional DAVI-isolated 6500-pound helicopter.

In these series of tests, the first tests conducted were on the nonisolated vehicle. The tests were first conducted on the nonisolated vehicle to obtain a base for comparison of results on the isolated vehicle and also to determine a force level in at least one direction of excitation sufficient to produce a minimum of $\pm$0.2 g level of acceleration at either the nose (station 50) or the cg (station 170) of the helicopter. It was determined that an excitation force level of $\pm$250 pounds was sufficient to produce the desired acceleration levels at 14.7 Hertz (n/rev of the three-bladed configuration) and at 19.8 Hertz (n/rev of the four-bladed configuration). However, at 10.8 (n/rev of the two-bladed configuration), an excitation force of $\pm$500 pounds was required to produce

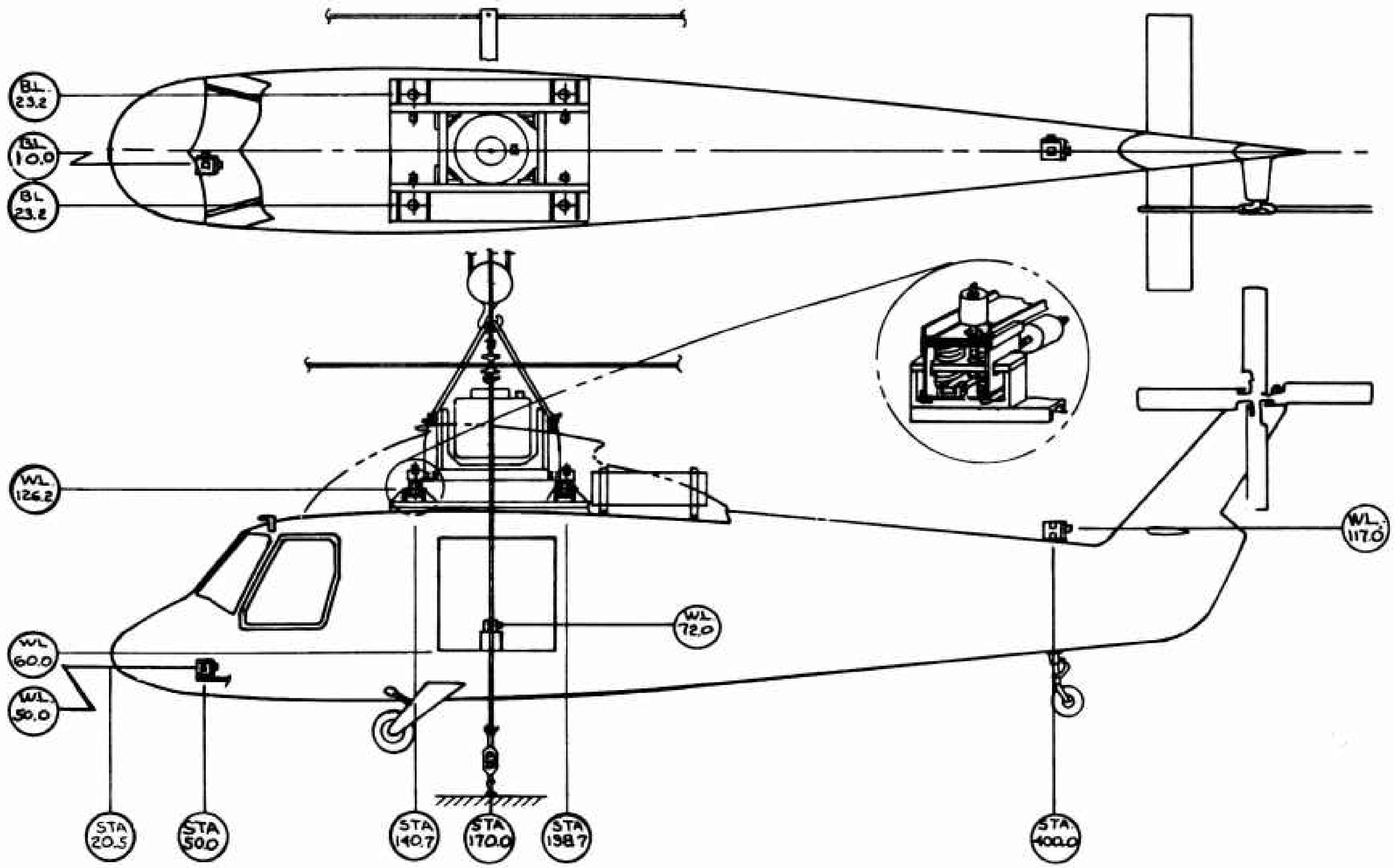


Figure 16. Accelerometer Locations.

TABLE XIII. TESTS CONDUCTED			
Number of Blades	Direction of Excitation	DAVI Antiresonant Frequency (Hertz)	Frequency Range (Hertz)
2,3,4	Vertical	Nonisolated (isolation system locked out)	5-45
2,3,4	Longitudinal	Nonisolated (isolation system locked out)	5-45
2,3,4	Lateral	Nonisolated (isolation system locked out)	5-45
4	Vertical	19.8	5-45
4	Longitudinal	19.8	5-45
4	Lateral	19.8	5-45
3	Vertical	14.7	5-35
3	Longitudinal	14.7	5-35
3	Lateral	14.7	5-35
2	Vertical	10.8	5-25
2	Longitudinal	10.8	5-25
2	Lateral	10.8	5-25

the desired acceleration levels; therefore, two series of nonisolated tests were run: one series up to 45 Hertz at ±250 pounds for the three- and four-bladed configurations and one series up to 25 Hertz at ±500 pounds for the two-bladed configuration.

Using the excitation force level of ±250 pounds, a frequency survey was made on the nonisolated vehicle from 5 Hertz to 45 Hertz in approximately 1-Hertz increments. At the predominant excitation frequencies of 1/rev, n/rev, and 2n/rev and natural frequencies, data at smaller increments were taken. The force level was reduced at frequencies where excessive vibration occurred such as at the natural frequencies. However, for plotting purposes, the data were corrected to a ±250-pound excitation force assuming a linear structure and response. This procedure was followed for the ±500-pound excitation force except that the vibration survey was made from 5 Hertz to 25 Hertz.

For the isolated vehicle, the DAVI was tuned to the appropriate n/rev frequency, and a vibration survey was made with the same force level. For the four-bladed configuration, the survey was made from 5 Hertz to 45 Hertz; for the three-bladed configuration, the survey was made from 5 Hertz to 35 Hertz; and for the two-bladed configuration, the survey was made from 5 Hertz to 25 Hertz.

TEST RESULTS

Three-Bladed Helicopter

The weights on the DAVI inertia bars were preset to the values obtained from the tuning rig to obtain an antiresonant frequency of 14.8 Hertz, as shown in Figure 10. Preliminary testing was then done and minor adjustments were made to the inertia bar weight to obtain the desired antiresonant frequency of 14.8 Hertz, which is the predominant excitation frequency of a three-bladed, 6500-pound helicopter. This resulted in the parameters for the three-dimensional DAVI isolation system as shown in Table XIV. In this table, the weight of the unidirectional inertia bar rod is 2.56 pounds and the weight of the movable weight is 17.5 pounds. The weight of the in-plane inertia bar rod is 3.25 pounds and the weight of the movable weight is 17.5 pounds.

Also, the preliminary testing indicated some undesirable rotation at the DAVI mounts of the upper body. The upper body was then stiffened by adding an angle between the two forward DAVI's and the two aft DAVI's as shown in Figure 17.

TABLE XIV. PARAMETERS OF DAVI ISOLATION SYSTEM FOR A THREE-BLADED HELICOPTER					
Direction	Spring Rate (lb/in.)	Static Deflection (in.)	r (in.)	R (in.)	DAVI Inertia Bar Weight (lb)
Vertical	15,780	.082	2	5.71	20.06
In-Plane	17,483	-	2	7.09	20.75

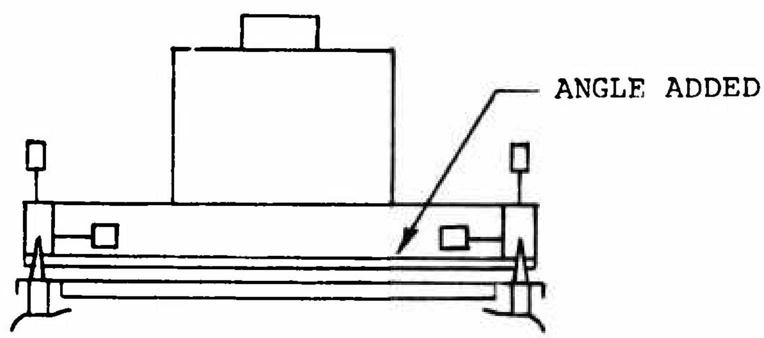


Figure 17. Angle Stiffening at Upper Body.

Figures 18, 19, and 20 show the results obtained for the non-isolated and DAVI-isolated three-bladed helicopter. It is seen from these figures that excellent results were obtained for the vertical and longitudinal directions of excitation. It is seen from Figures 18 and 19 that not only were very low vibration levels obtained at or near the tuned frequency of the DAVI, but a broad band of isolation was achieved. The reduction in vibration obtained for the lateral direction of excitation was not as good. However, in this direction, the response of the helicopter was a minimum and the vibration levels were low for both the nonisolated and the isolated helicopters. Even at these low vibration levels, isolation was achieved in most locations along the fuselage.

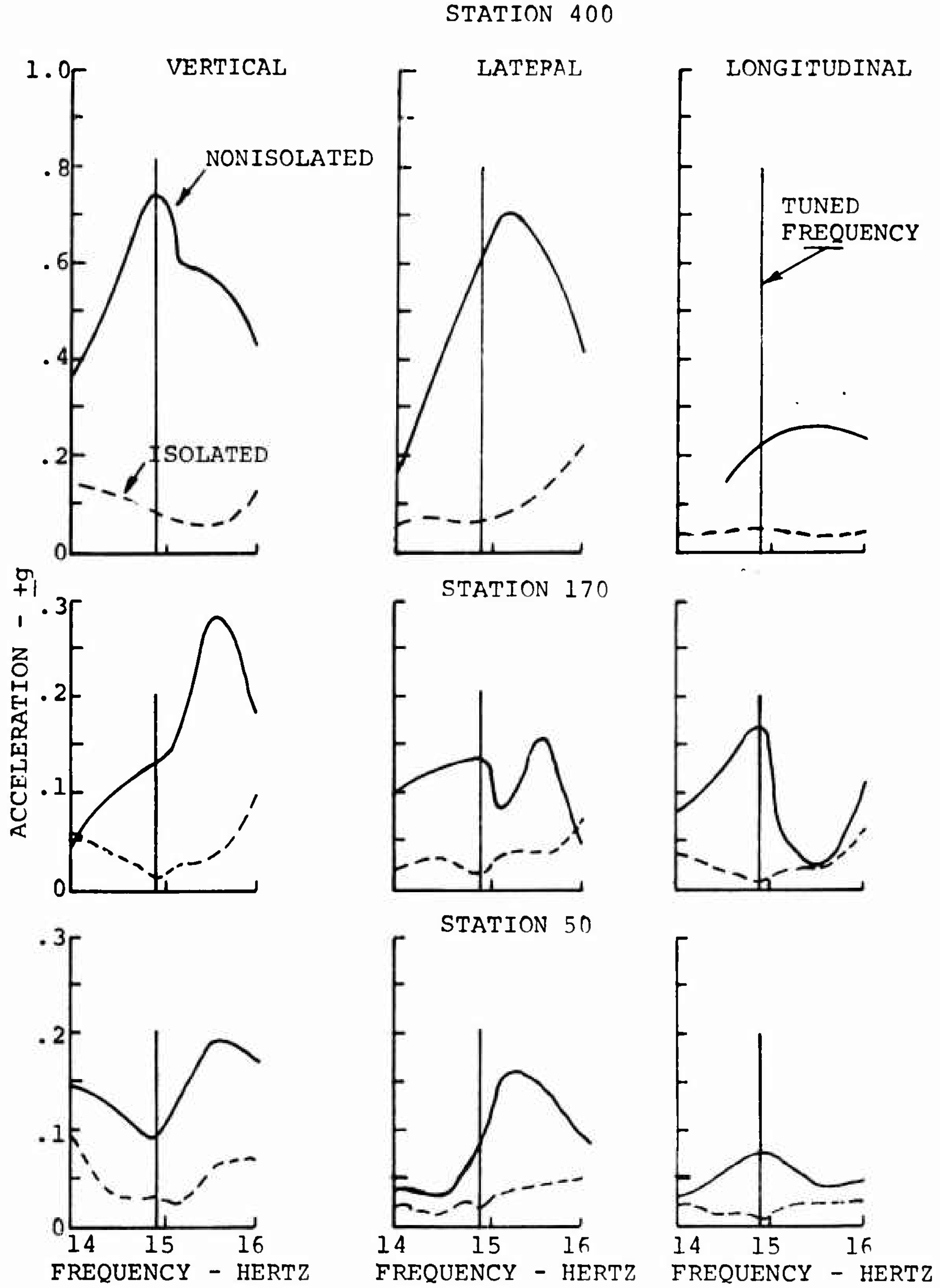


Figure 18. Responses of a Nonisolated and DAVI-Isolated Three-Bladed Helicopter for Vertical Excitation.

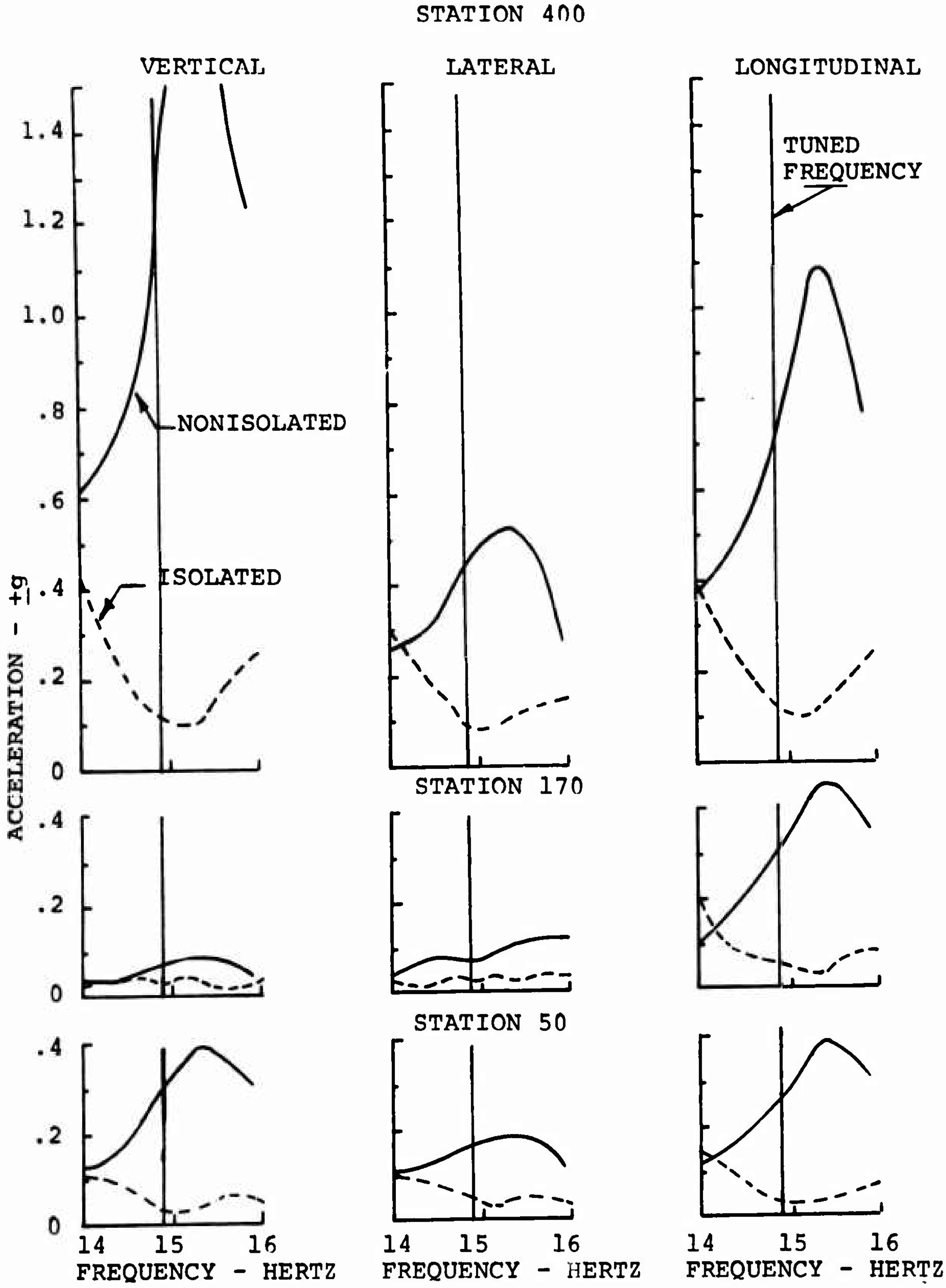


Figure 19. Responses of a Nonisolated and DAVI-Isolated Three-Bladed Helicopter for Longitudinal Excitation.

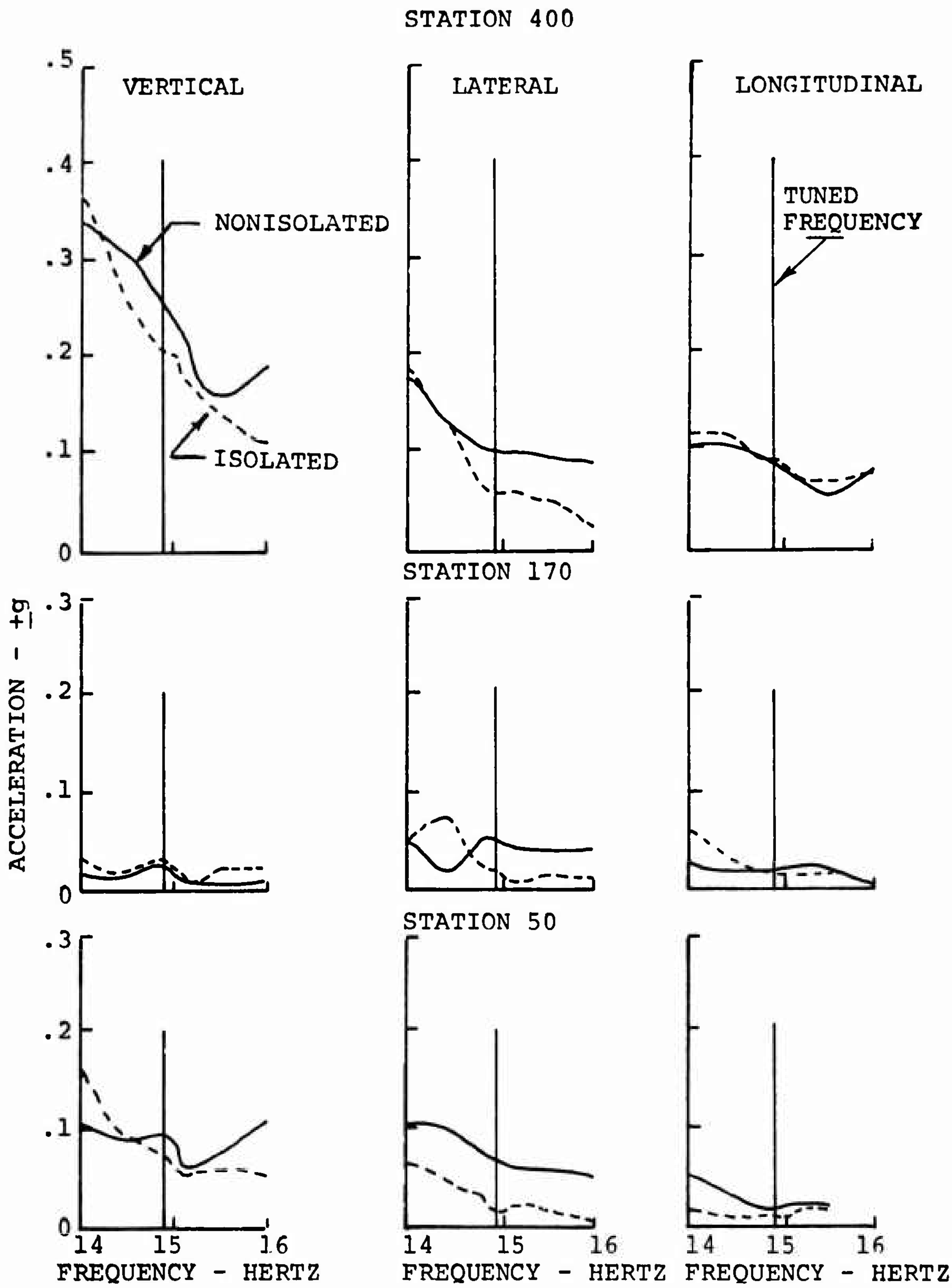


Figure 20. Responses of a Nonisolated and DAVI-Isolated Three-Bladed Helicopter for Lateral Excitation.

Figures 21, 22, and 23 show the effectivity of the DAVI isolation system for a three-bladed helicopter. Effectivity, as presented in these results, is the acceleration obtained on the nonisolated helicopter divided by the accelerations obtained on the DAVI-isolated helicopter. The higher the effectivity, the greater the isolation. Effectivity less than one would indicate amplification. These figures show that excellent isolation was obtained for the vertical and longitudinal directions of excitation. It is also seen that isolation was obtained in the lateral direction of excitation even though the response of the nonisolated helicopter was low. It is significant to point out that the isolation was not just obtained at a single location on the fuselage, but throughout the structure, thus insuring an overall low vibration level.

Table XV shows the results obtained for the one-per-rev, three-per-rev, and six-per-rev excitation frequencies, which would be the significant excitation frequencies of the three-bladed helicopter. The results are predicted on the rotor excitations conforming to the criterion stated in Reference 6. More specifically, the one-per-rev and 2n-per-rev excitations (forces) are assumed to be 10 percent and 40 percent of the n-per-rev excitation, respectively. Thus, the results are reported for shaking the helicopter with an excitation force of ±25 pounds at the one-per-rev frequency and with an excitation force of ±100 pounds at the six-per-rev excitation frequency.

It is seen from Table XV that excellent results were obtained at three-per-rev, which is the predominant excitation of a three-bladed helicopter. The results show that for the DAVI-isolated helicopter, very low vibration levels were obtained for all directions of excitation.

Table XV also shows that the one-per-rev vibration levels are low. It is seen that essentially no isolation was obtained, which is to be expected, since the DAVI isolation system was designed to have its natural frequencies above the one-per-rev excitation frequency; therefore, amplification would be expected. However, none of the one-per-rev vibration levels obtained on the DAVI-isolated helicopter were high.

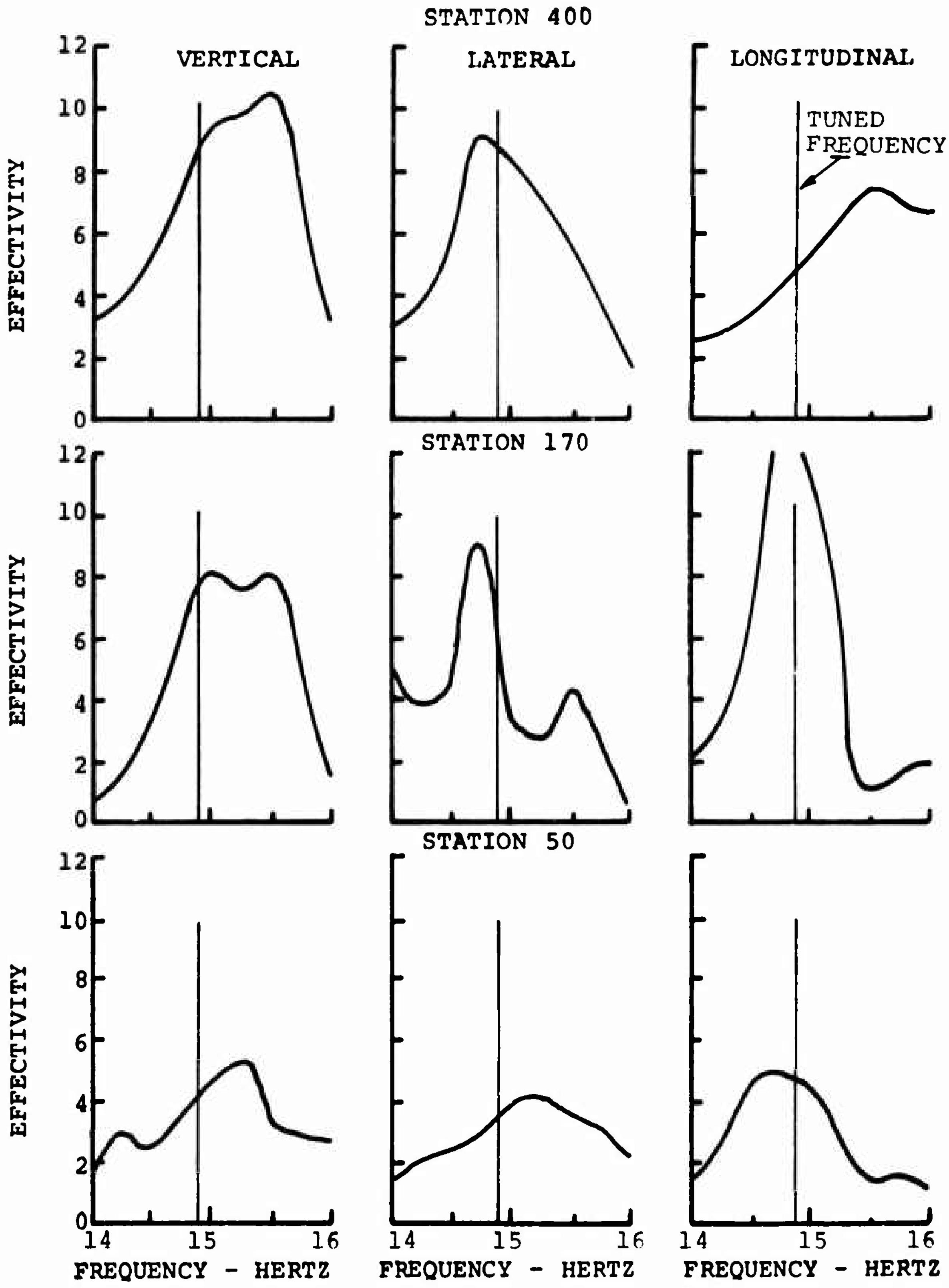


Figure 21. Effectivity of a DAVI-Isolated Three-Bladed Helicopter for Vertical Excitation.

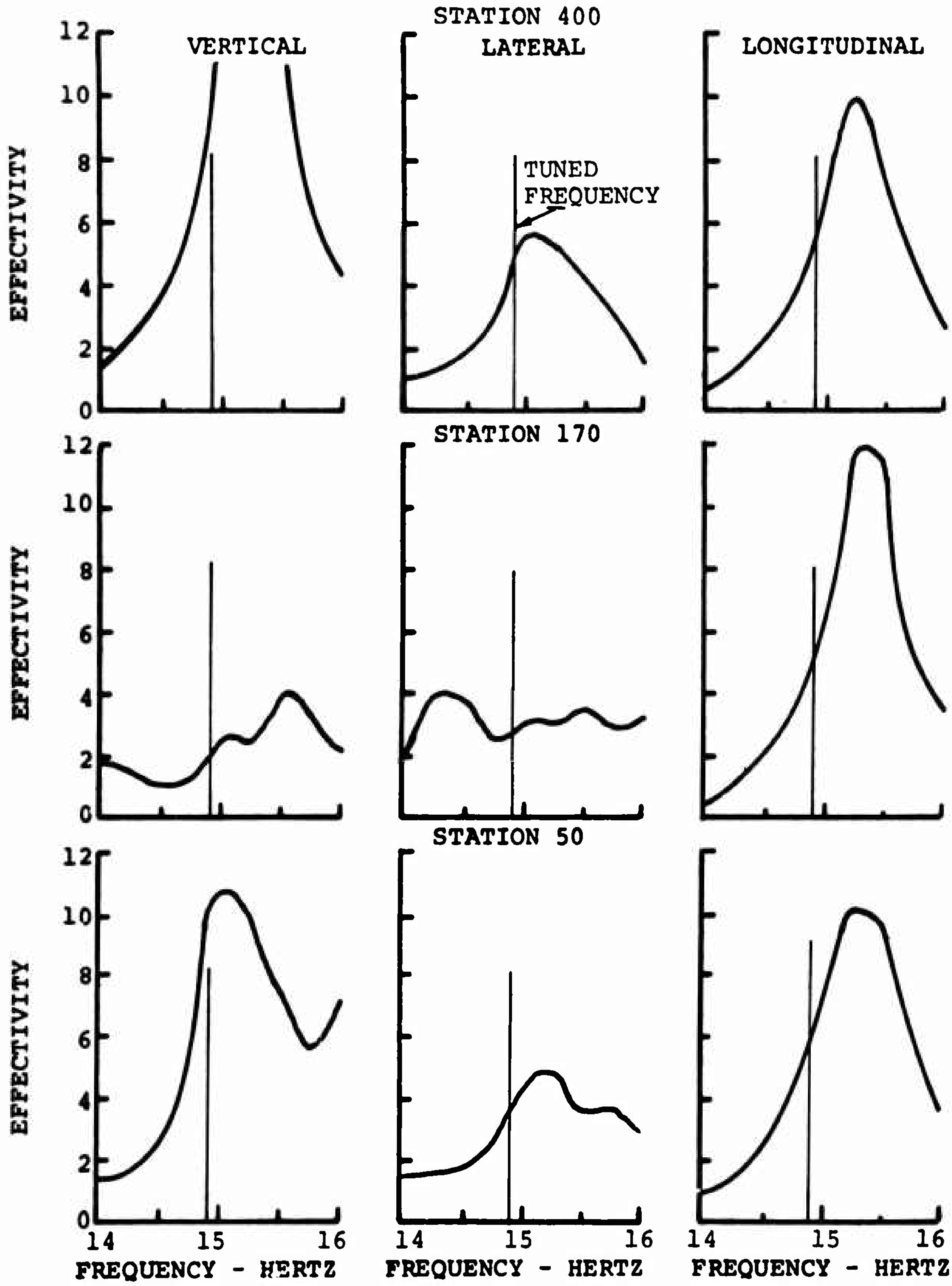


Figure 22. Effectivity of a DAVI-Isolated Three-Bladed Helicopter for Longitudinal Excitation.

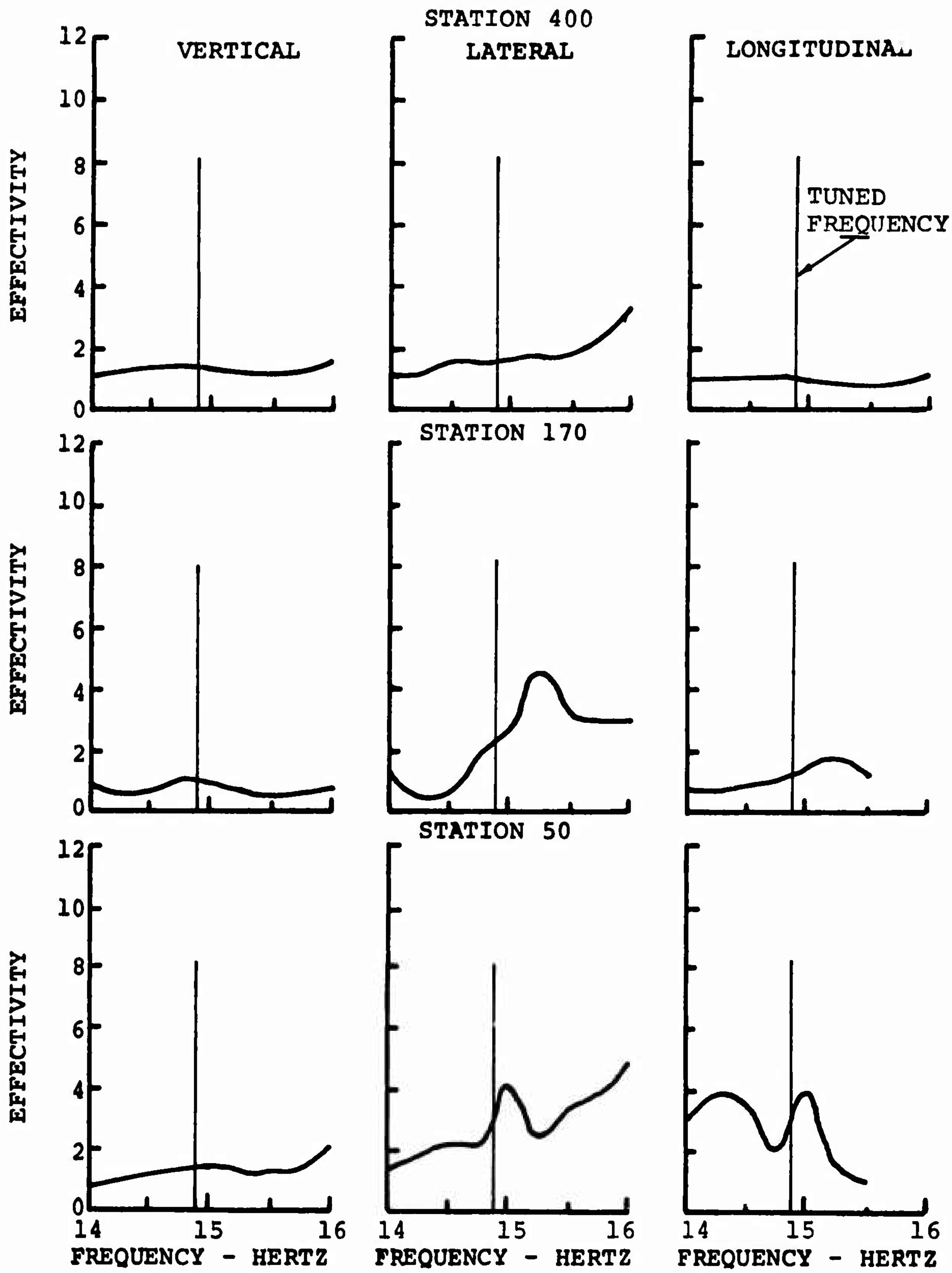


Figure 23. Effectivity of a DAVI-Isolated Three-Bladed Helicopter for Lateral Excitation.

TABLE XV. PREDOMINANT VIBRATION LEVELS OF THE THREE-BLADED HELICOPTER

Pickup Location		1-Per-Rev (±g)			3-Per-Rev (±g)			6-Per-Rev (±g)		
Sta	Direction	Non-Iso	Iso	T*	Non-Iso	Iso	T*	Non-Iso	Iso	T*
Vertical Excitation										
	Vert	.005	.005	1.00	.742	.088	.12	.065	.015	.23
400	Long.	.002	.001	.50	.223	.038	.17	.056	.067	1.20
	Lat	.001	.001	1.00	.616	.072	.12	.058	.039	.67
	Vert	.004	.005	1.25	.128	.013	.10	.115	.055	.48
170	Long.	.001	.001	1.00	.166	.010	.06	.151	.046	.30
	Lat	.001	.001	1.00	.134	.019	.14	.087	.055	.63
	Vert	.005	.009	1.80	.090	.028	.31	.065	.042	.65
50	Long.	.001	.001	1.00	.076	.010	.13	.028	.033	1.18
	Lat	.001	.001	1.00	.092	.020	.22	.049	.031	.63
Longitudinal Excitation										
	Vert	.010	.010	1.00	1.253	.148	.12	.048	.048	1.00
400	Long	.007	.009	1.29	.734	.157	.21	.068	.113	1.66
	Lat	.001	.002	2.00	.443	.137	.31	.060	.073	1.22
	Vert	.001	.002	2.00	.067	.044	.66	.058	.092	1.59
170	Long.	.005	.006	1.20	.282	.065	.23	.108	.189	1.73
	Lat	.001	.001	1.00	.069	.033	.48	.024	.054	2.25
	Vert	.006	.004	.67	.301	.065	.22	.036	.041	1.14
50	Long.	.003	.003	1.00	.249	.060	.24	.041	.075	1.83
	Lat	.001	.002	2.00	.160	.063	.39	.026	.024	.92
Lateral Excitation										
	Vert	.002	.002	1.00	.268	.206	.77	.015	.010	.67
400	Long.	.001	.001	1.00	.093	.083	.89	.028	.007	.25
	Lat	.003	.001	.33	.105	.061	.58	.036	.019	.03
	Vert	.001	.001	1.00	.027	.035	1.30	.025	.016	.64
170	Long.	.001	.001	1.00	.019	.019	1.00	.020	.014	.70
	Lat	.003	.003	1.00	.054	.023	.43	.010	.079	7.90
	Vert	.002	.001	.50	.099	.078	.79	.030	.010	.33
50	Long.	.002	.001	1.00	.014	.009	.64	.015	.007	.47
	Lat	.001	.003	3.00	.075	.019	.25	.023	.026	1.13

*T = Transmissibility; ratio isolated/nonisolated response.

Table XVI shows the relative deflection obtained between the rotor or upper body and the fuselage or isolated body for the three directions of excitation. These results are reported in a similar manner as in Table XV. That is, the results are reported for shaking the helicopter with an excitation force of ±25 pounds at the one-per-rev frequency and with an excitation force of ±100 pounds at the six-per-rev excitation frequency.

Table XVI shows the relative deflection in the system to be small. It is seen that the greatest deflection occurred at the three-per-rev excitation and that the vertical relative deflection for all directions of excitation was greater than either the longitudinal or the late.. l relative deflections. The small vertical deflections that were obtained for the longitudinal and lateral directions of excitation indicate a minimum of relative rotation between the upper body and lower bodies. These small angular and translational deflections should present no problems to couplings and shafting between the engine and transmission.

Four-Bladed Helicopter

The predominant excitation frequency of the four-bladed rotor configuration simulated in this series of tests was 19.8 Hertz. For these tests, lighter movable weights of 9.5 pounds and 8.0 pounds were used on the 2.56-pound unidirectional and 3.25-pound in-plane inertia rods, respectively. Since these weights were not tuned on the DAVI tuning rig, preliminary testing on the helicopter was required to obtain the proper antiresonant frequency. This tuning was accomplished with the vertical direction of excitation and moving the weights on the four unidirectional inertia bars until minimum vibration was obtained. Tuning for an in-plane direction of excitation was done in a similar manner. This resulted in the parameters for the three-dimensional DAVI isolation system as shown in Table XVII.

Figures 24, 25, and 26 show the results obtained for the non-isolated and DAVI-isolated four-bladed helicopter. In Figures 24 and 25, it is seen that two tests were run in this frequency range for the DAVI isolation system. The dashed lines show the first series of tests, and the broken lines are the results obtained after replacing the bearings in the DAVI's.

TABLE XVI. RELATIVE DEFLECTION IN THE DAVI ISOLATION SYSTEM FOR A THREE-BLADED HELICOPTER

DAVI Location	Direction	Relative Deflection ($\pm$in.) 1-Per-Rev	3-Per-Rev	6-Per-Rev
Vertical Excitation				
Left Fwd	Vertical	.0006	.0121	.0010
	Longitudinal	-	-	-
	Lateral	-	.0012	.0001
Rt Fwd	Vertical	.0004	.0162	.0006
	Longitudinal	-	.0006	.0005
	Lateral	-	.0051	.0001
Rt Aft	Vertical	.0004	.0106	.0004
	Longitudinal	-	.0010	.0004
	Lateral	-	-	-
Left Aft	Vertical	.0005	.0156	-
	Longitudinal	-	.0013	.0001
	Lateral	-	.0006	-
Longitudinal Excitation				
Left Fwd	Vertical	.0004	.0156	.0014
	Longitudinal	-	.0010	.0022
	Lateral	-	.0040	-
Rt Fwd	Vertical	.0002	.0131	.0006
	Longitudinal	.0002	.0048	.0030
	Lateral	-	.0018	.0009
Rt Aft	Vertical	.0001	.0078	.0002
	Longitudinal	.0002	.0030	.0032
	Lateral	-	.0029	.0002
Left Aft	Vertical	.0002	.0210	.0021
	Longitudinal	.0001	.0030	.0016
	Lateral	-	.0005	.0001

TABLE XVI - Continued				
Lateral Excitation				
DAVI Location	Direction	Relative Deflection ($\pm$in.)		
		1-Per-Rev	3-Per-Rev	6-Per-Rev
Left Fwd	Vertical	.0005	.0120	.0026
	Longitudinal	-	-	-
	Lateral	.0001	.0003	.0003
Rt Fwd	Vertical	.0002	.0076	.0006
	Longitudinal	-	.0003	.0006
	Lateral	.0002	.0018	.0001
Rt Aft	Vertical	.0003	.0046	.0003
	Longitudinal	-	.0001	-
	Lateral	-	.0001	-
Left Aft	Vertical	.0005	.0056	.0013
	Longitudinal	-	.0004	.0001
	Lateral	.0001	.0007	.0008

TABLE XVII. PARAMETERS OF A DAVI ISOLATION SYSTEM FOR A FOUR-BLADED HELICOPTER

Direction	Spring Rate (lb/in.)	Static Deflection (in.)	r (in.)	R (in.)	DAVI Inertia Bar Weight (lb)
Vertical	15,780	.082	2	6.00	12.06
In-Plane	17,483	-	2	5.70	11.25

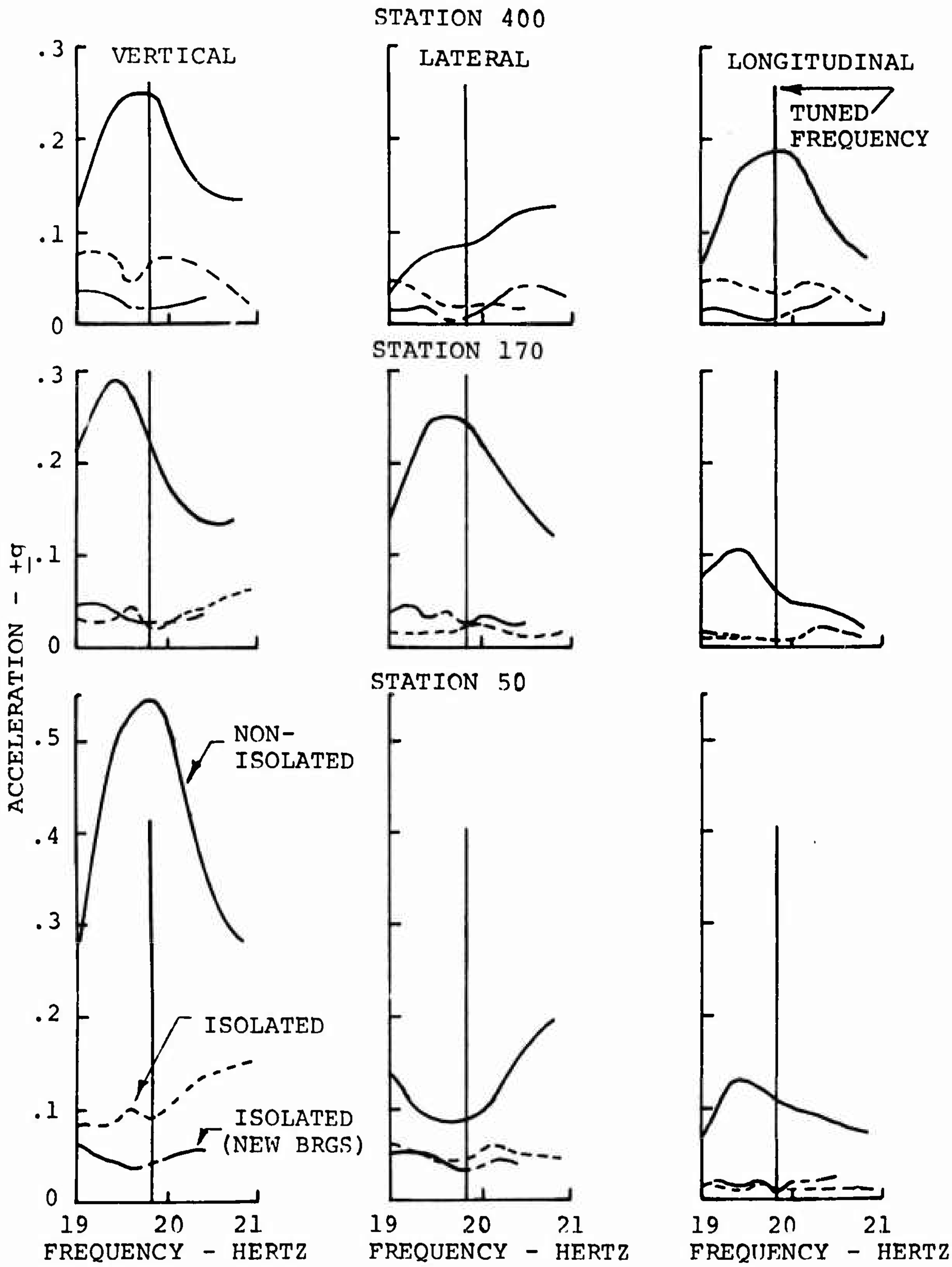


Figure 24. Responses of a Nonisolated and DAVI-Isolated Four-Bladed Helicopter for Vertical Excitation.

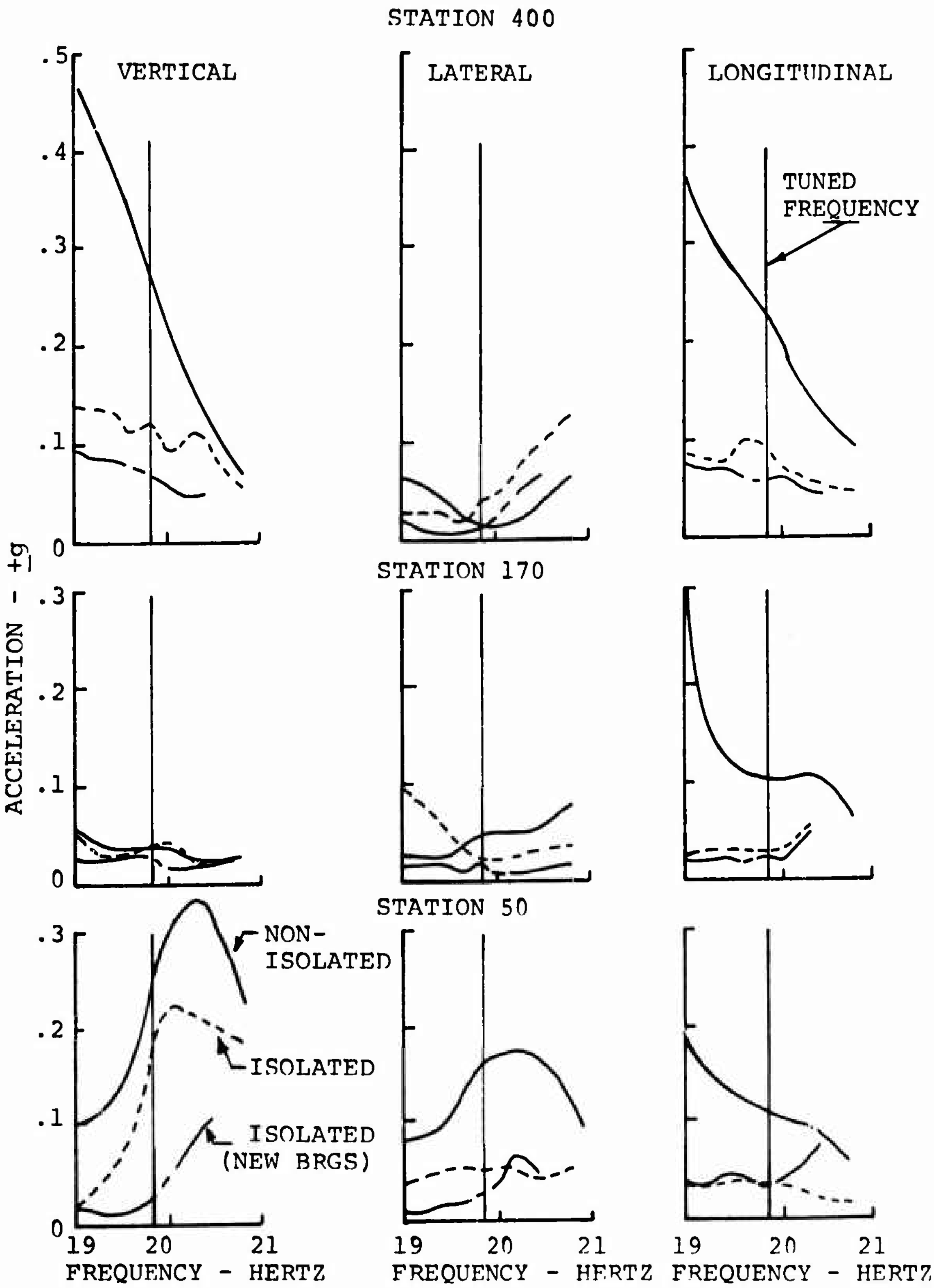


Figure 25. Responses of a Nonisolated and DAVI-Isolated Four-Bladed Helicopter for Longitudinal Excitation.

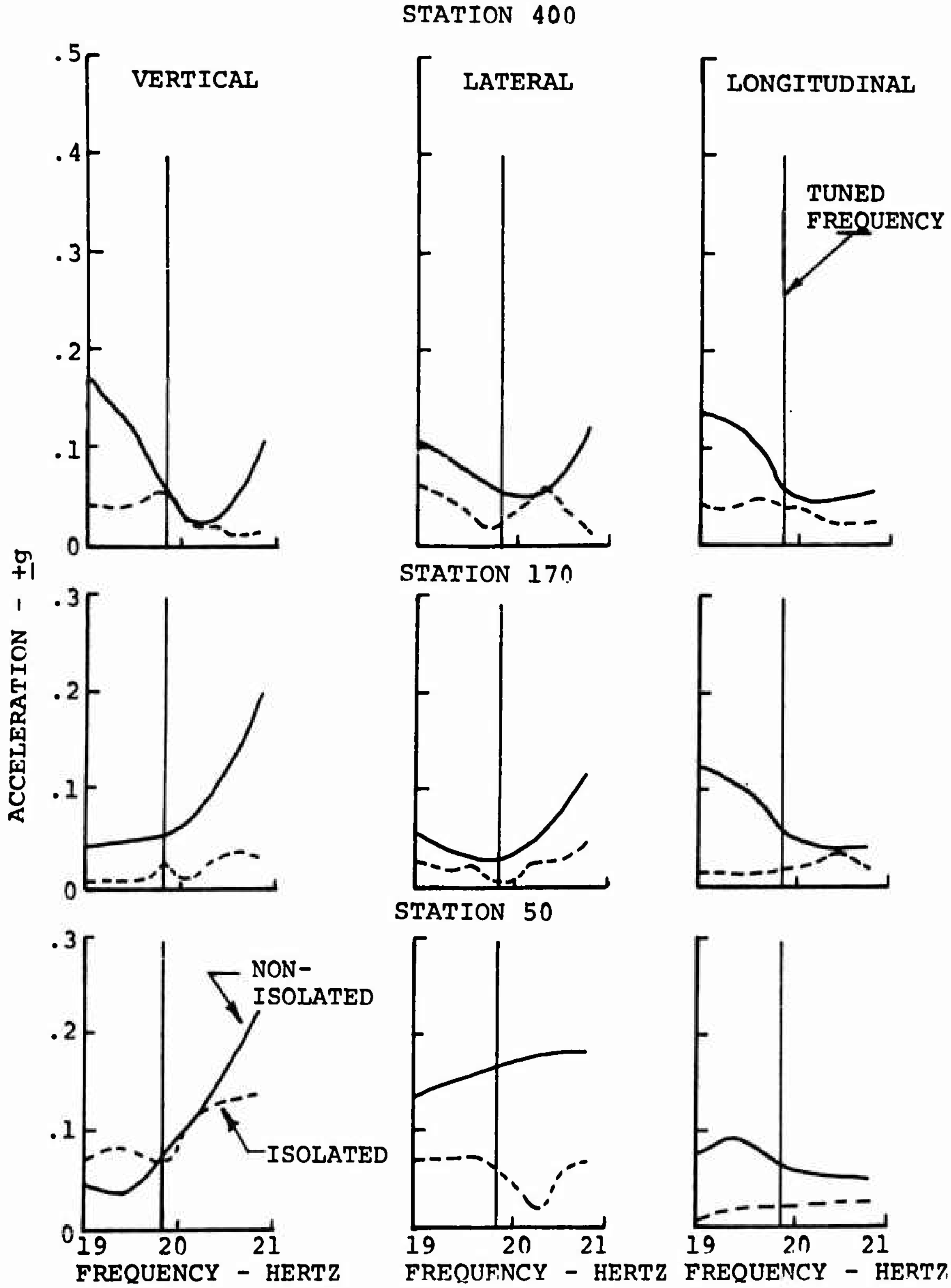


Figure 26. Responses of a Nonisolated and DAVI-Isolated Four-Bladed Helicopter for Lateral Excitation.

In comparing Figures 24 and 25, for the first series of tests, it is seen that although good to excellent reduction in vibration was obtained, the antiresonance excitation for the longitudinal direction of excitation occurred at a frequency slightly below 19 Hertz, and it did not coincide with the antiresonant frequency obtained for the vertical direction of excitation. The bearings in the DAVI were then changed and excellent results were obtained.

It is seen in Figures 24 and 25 that in most locations, not only were very low vibration levels obtained at or near the tuned frequency of the DAVI, but a broad band of isolation was achieved.

In Figure 26, it is seen that for the lateral direction of excitation, the responses of the nonisolated helicopter and DAVI-isolated helicopter were low. However, isolation was obtained.

Figures 27, 28, and 29 show the effectivity of the DAVI isolation system for a four-bladed helicopter. These figures show that excellent isolation was obtained for the vertical and longitudinal directions of excitation. It is also seen that isolation was obtained in the lateral direction of excitation even though the response of the nonisolated helicopter was low. It is further seen that isolation was obtained at all locations on the fuselage, thus insuring an overall low vibration level.

Table XVIII shows the results obtained for one-per-rev, four-per-rev, and eight-per-rev, which would be the significant excitation frequencies of the four-bladed helicopter. The results are reported for one-per-rev, being one-tenth the value of the forcing function of four-per-rev, and eight-per-rev, being four-tenths the value of the four-per-rev forcing function.

It is seen from Table XVIII that excellent results were obtained at four-per-rev for the vertical direction of excitation. Good reductions of vibration levels were obtained at four-per-rev for the longitudinal direction of excitation. The reduction was not as impressive as for the vertical direction of excitation because in this series of tests the antiresonant frequency was below the four-per-rev excitation frequency.

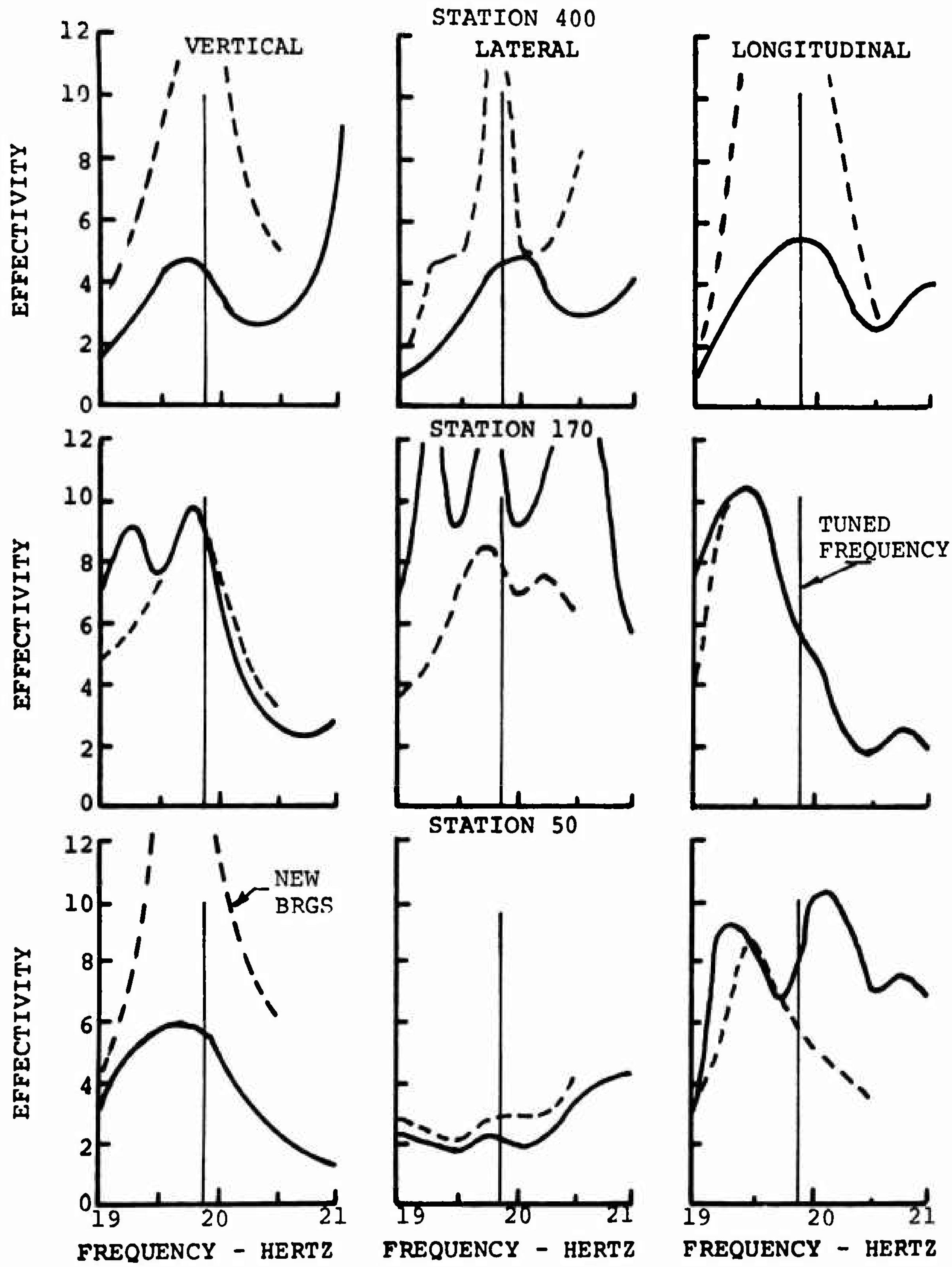


Figure 27. **Effectivity of a DAVI-Isolated Four-Bladed Helicopter for Vertical Excitation.**

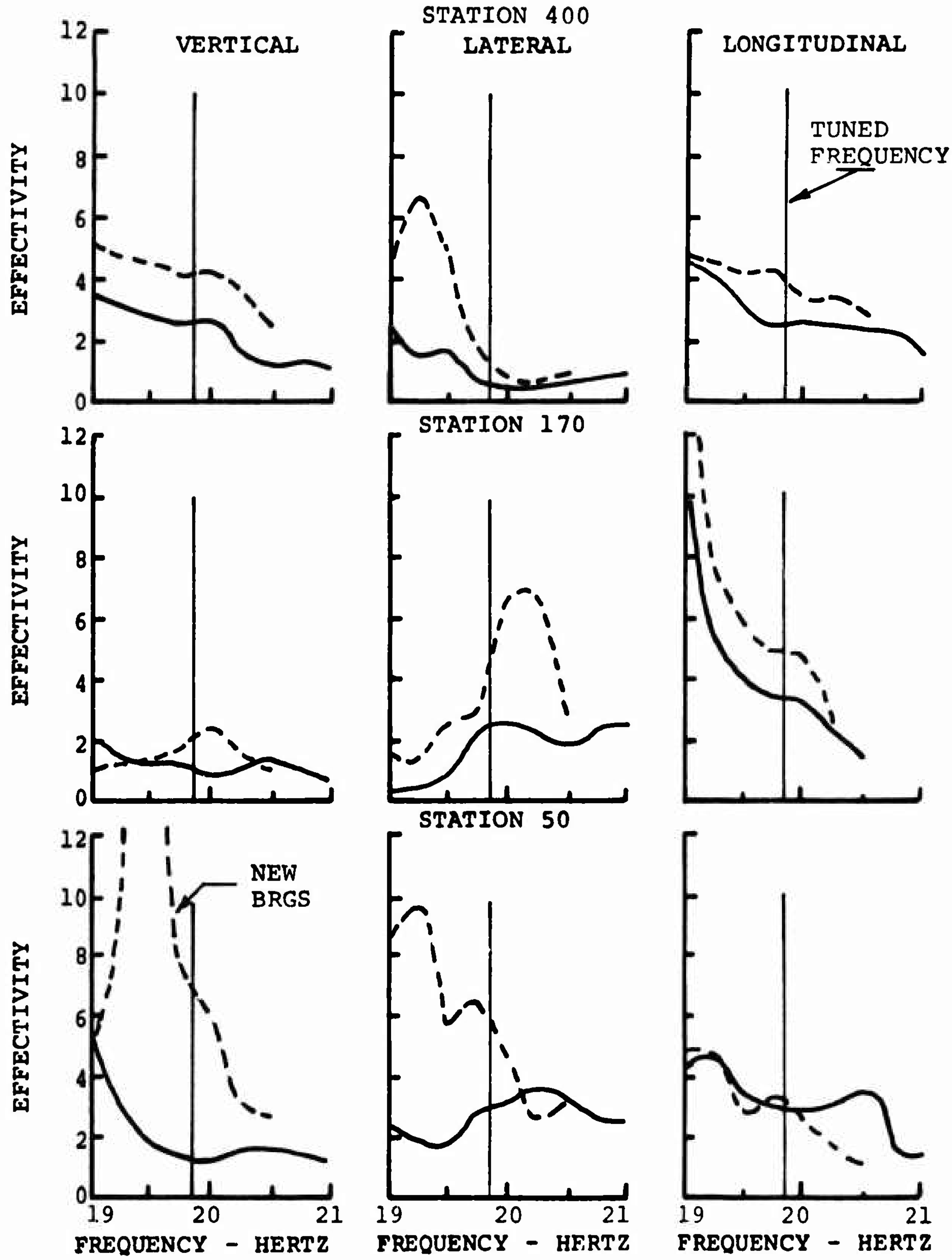


Figure 28. Effectivity of a DAVI-Isolated Four-Bladed Helicopter for Longitudinal Excitation.

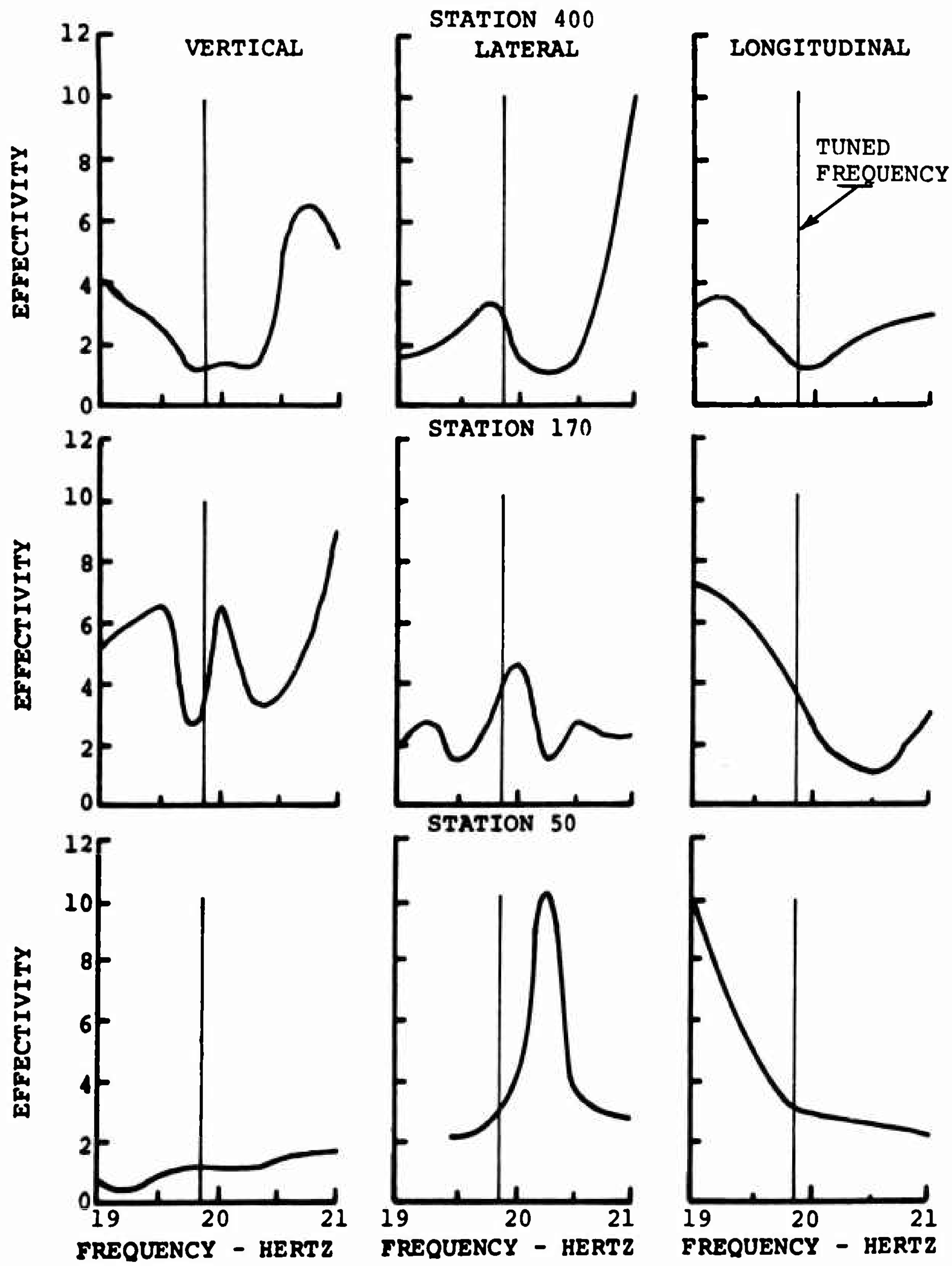


Figure 29. Effectivity of a DAVI-Isolated Four-Bladed Helicopter for Lateral Excitation.

TABLE XVIII. PREDOMINANT VIBRATION LEVELS OF THE FOUR-BLADED HELICOPTER

Pickup Location		1-Per-Rev ($\pm g$)			4-Per-Rev ($\pm g$)			8-Per-Rev ($\pm g$)		
Sta	Direction	Non-Iso	Iso	T*	Non-Iso	Iso	T*	Non-Iso	Iso	T*
Vertical Excitation										
	Vert	.005	.006	1.20	.244	.048	.20	.104	.099	.95
400	Long.	.002	.001	.50	.191	.041	.21	.029	.026	.90
	Lat	.001	.001	1.00	.086	.022	.26	.027	.010	.37
	Vert	.004	.005	1.25	.200	.022	.11	.051	.049	.96
170	Long.	.001	.001	1.00	.051	.012	.24	.473	.346	.73
	Lat	.001	.001	1.00	.237	.017	.07	.358	.280	.78
	Vert	.005	.005	1.00	.543	.094	.17	.055	.068	1.23
50	Long	.001	.001	1.00	.103	.012	.12	.024	.024	1.00
	Lat	.001	.001	1.00	.095	.050	.53	.003	.024	8.00
Longitudinal Excitation										
	Vert	.010	.009	.90	.283	.121	.43	.124	.129	1.04
400	Long.	.007	.007	1.00	.236	.100	.42	.027	.020	.74
	Lat	.001	.001	1.00	.011	.043	3.91	.014	.061	4.35
	Vert	.001	.001	1.00	.040	.037	.92	.057	.095	1.67
170	Long.	.005	.004	.80	.101	.030	.30	.199	.400	2.00
	Lat	.001	.001	1.00	.047	.019	.40	.226	.378	1.67
	Vert	.006	.006	1.00	.265	.182	.69	.054	.132	2.44
50	Long.	.003	.003	1.00	.119	.040	.34	.011	.018	1.63
	Lat	.001	.001	1.00	.165	.054	.33	.026	.037	1.42
Lateral Excitation										
	Vert	.002	.001	.50	.052	.025	.48	.139	.064	.46
400	Long.	.001	.001	1.00	.055	.040	.73	.029	.013	.45
	Lat	.003	.004	1.33	.052	.038	.73	.058	.015	.26
	Vert	.001	.001	1.00	.052	.028	.54	.028	.025	.89
170	Long.	.001	.001	1.00	.070	.020	.29	.147	.238	1.62
	Lat	.003	.003	1.00	.029	.010	.34	.202	.325	1.61
	Vert	.002	.001	.50	.079	.074	.94	.056	.091	1.63
50	Long.	.001	.001	1.00	.061	.020	.33	.019	.012	.63
	Lat	.001	.001	1.00	.161	.064	.40	.019	.014	.74

*T = Transmissibility; ratio isolated/nonisolated response.

Reduction of vibration levels was obtained at four-per-rev for the lateral direction of excitation. The percentage of reduction of the vibration level was not as good as in the other directions. However, the responses of the nonisolated helicopter and the DAVI-isolated helicopter were low for the lateral direction of excitation.

Table XVIII also shows that with the DAVI isolation system, there was no significant difference in the one-per-rev vibration levels from those obtained on the nonisolated helicopter. This is to be expected since the DAVI isolation system was designed to have its natural frequencies above the one-per-rev excitation frequencies. Actually, modest amplification should be anticipated. In both cases the responses were very low.

Table XIX shows the results obtained after the bearings in the DAVI were replaced. These results show that excellent reduction in vibration level was obtained for the four-per-rev excitation with the DAVI isolation system. Tests at one-per-rev and eight-per-rev with new bearings installed were not conducted. However, from the marked improvement in the already excellent four-per-rev improvement, it is reasonable to conclude that proportional improvements at one-per-rev and eight-per-rev would also be experienced.

Table XX shows the relative deflection obtained between the rotor or upper body and the fuselage or isolated body for the three directions of excitation. The results are reported for shaking the helicopter with an excitation force of ± 25 pounds at the one-per-rev frequency and with an excitation force of ± 100 at the eight-per-rev frequency.

Table XX shows that the relative deflections in the system were small. It is seen that the greatest deflection occurred at the four-per-rev excitation. These small deflections should present no problems to coupling and shafting between the engine and transmission.

TABLE XIX. FOUR-PER-REV PREDOMINANT VIBRATION LEVELS OF THE FOUR-BLADED HELICOPTER

Pickup Location		4-Per-Rev ($\pm$g)		
Station	Direction	Non-Isolated	Isolated	T*
Vertical Excitation				
	Vertical	.244	.020	.08
400	Longitudinal	.191	.005	.03
	Lateral	.086	.005	.06
	Vertical	.200	.029	.15
170	Longitudinal	.051	.010	.20
	Lateral	.237	.025	.11
	Vertical	.543	.043	.08
50	Longitudinal	.103	.010	.10
	Lateral	.095	.033	.35
Longitudinal Excitation				
	Vertical	.283	.067	.24
400	Longitudinal	.236	.058	.25
	Lateral	.011	.014	1.27
	Vertical	.040	.027	.68
170	Longitudinal	.101	.029	.29
	Lateral	.047	.019	.40
	Vertical	.265	.027	.10
50	Longitudinal	.119	.039	.33
	Lateral	.165	.031	.19

*T = Transmissibility; ratio isolated/nonisolated response.

TABLE XX. RELATIVE DEFLECTION IN THE DAVI ISOLATION SYSTEM FOR A FOUR-BLADED HELICOPTER

DAVI Location	Direction	Relative Deflection ($\pm$in.) 1-Per-Rev	4-Per-Rev	8-Per-Rev
Vertical Excitation				
Left Fwd	Vertical	.0005	.0068	.0011
	Longitudinal	-	-	-
	Lateral	-	.0004	.0001
Rt Fwd	Vertical	.0003	.0083	.0002
	Longitudinal	-	.0002	.0001
	Lateral	-	.0011	.0001
Rt Aft	Vertical	.0004	.0006	.0001
	Longitudinal	-	.0005	-
	Lateral	-	.0010	-
Left Aft	Vertical	.0004	.0077	.0004
	Longitudinal	.0001	.0008	-
	Lateral	-	.0002	-
Longitudinal Excitation				
Left Fwd	Vertical	.0003	.0072	.0012
	Longitudinal	-	.0034	-
	Lateral	-	.0005	.0004
Rt Fwd	Vertical	.0001	.0042	.0002
	Longitudinal	.0002	.0052	.0001
	Lateral	-	.0021	.0006
Rt Aft	Vertical	.0001	.0006	-
	Longitudinal	.0001	.0013	-
	Lateral	-	.0004	-
Left Aft	Vertical	.0002	.0040	.0010
	Longitudinal	.0001	.0016	-
	Lateral	-	.0001	-

TABLE XX - Continued				
Lateral Excitation				
DAVI Location	Direction	Relative Deflection (±in.)		
		1-Per-Rev	4-Per-Rev	8-Per-Rev
Left Fwd	Vertical	.0003	.0150	.0004
	Longitudinal	-	.0004	-
	Lateral	.0001	.0021	.0004
Rt Fwd	Vertical	.0003	.0110	.0002
	Longitudinal	-	.0011	.0001
	Lateral	.0001	.0015	.0003
Rt Aft	Vertical	.0002	.0084	.0001
	Longitudinal	-	.0008	-
	Lateral	-	.0004	-
Left Aft	Vertical	.0003	.0114	.0002
	Longitudinal	-	.0010	-
	Lateral	.0001	.0010	.0001

Two-Bladed Helicopter

The movable weights of 17.5 pounds on the 2.56-pound unidirectional and 3.25-pound two-dimensional inertia bar rods were preset to the values obtained from the tuning rig to obtain an antiresonant frequency of 10.8 Hertz, as shown in Figure 11. The DAVI's were preset to this antiresonant frequency to more realistically represent the Army UH-1 helicopter rather than 9.9 Hertz, which was the antiresonant frequency analyzed and represented the statistical two-bladed helicopter of Reference 6. Preliminary testing was then done to refine the tuning at 10.8 Hertz. This resulted in the following characteristics for the three-dimensional DAVI isolation system as shown in Table XXI.

TABLE XXI. PARAMETERS OF A DAVI ISOLATION SYSTEM FOR A TWO-BLADED HELICOPTER

Direction	Spring Rate (lb/in.)	Static Deflection (in.)	r (in.)	R (in.)	DAVI Inertia Bar Weight (lb)
Vertical	15,780	.082	2	9.39	20.06
In-Plane	17,483	-	2	9.64	20.75

Figures 30, 31, and 32 show the results obtained for the nonisolated and DAVI-isolated two-bladed helicopter. It is seen in Figure 30 that a reduction of vibration was obtained at the antiresonant frequency of the DAVI. From this figure, it is seen that only the vertical accelerations of the nonisolated helicopter were of any great magnitude, and it was in this direction that the greatest reduction of vibration was obtained. The lateral and longitudinal responses of the nonisolated helicopter for the vertical excitation were very low. However, a reduction of vibration was obtained in these directions.

Figure 31 shows the results obtained for the longitudinal direction of excitation. It is seen that the maximum reduction of vibration was obtained at the tuned frequency of the DAVI isolation system. This reduction occurred in both the vertical and longitudinal accelerations, which had the greatest responses for the nonisolated helicopter. Although essentially no reduction of vibration was obtained in the lateral accelerations, both the nonisolated and DAVI-isolated helicopters had lateral accelerations of less than ± 0.05 g.

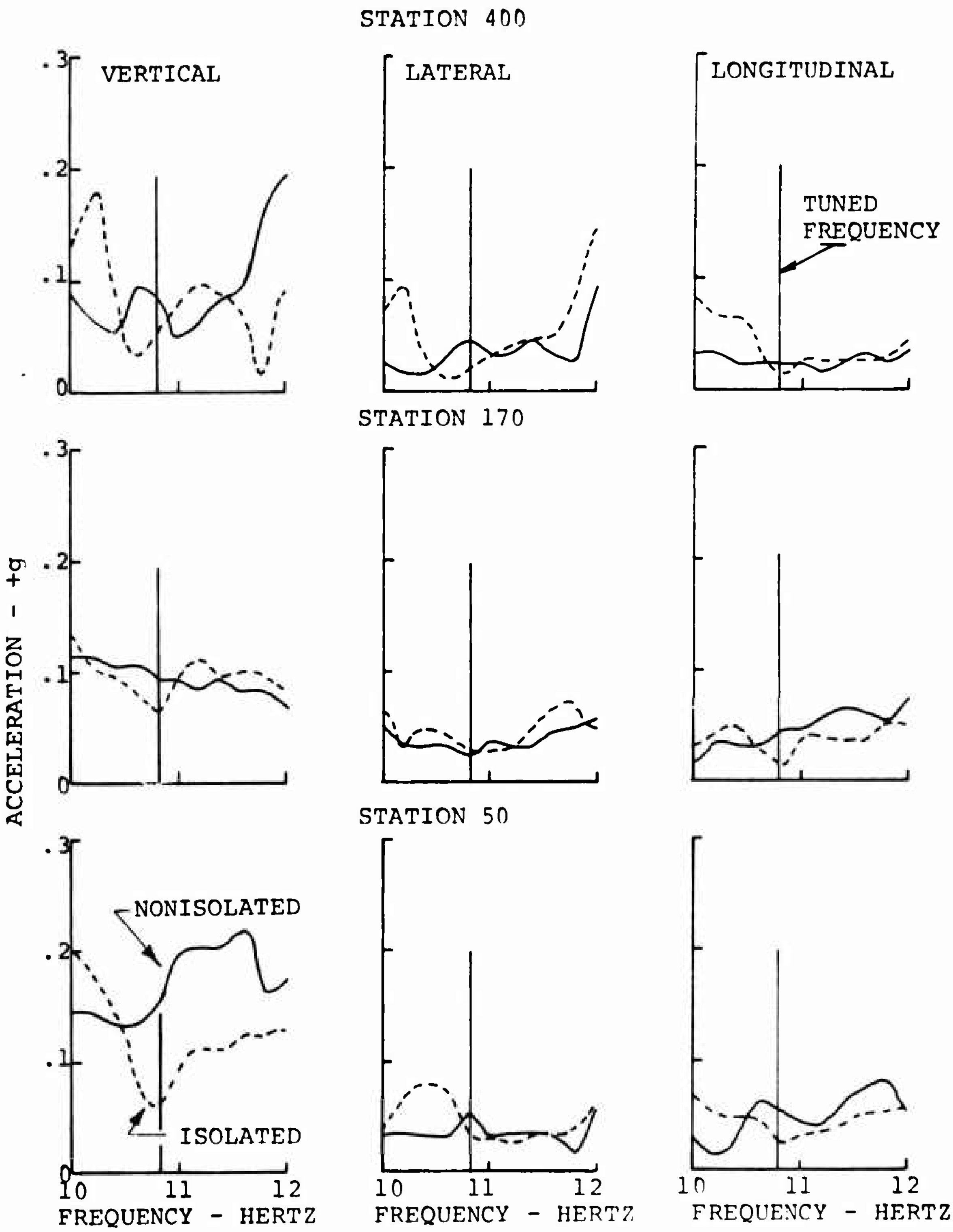


Figure 30. Responses of a Nonisolated and DAVI-Isolated Two-Bladed Helicopter for Vertical Excitation.

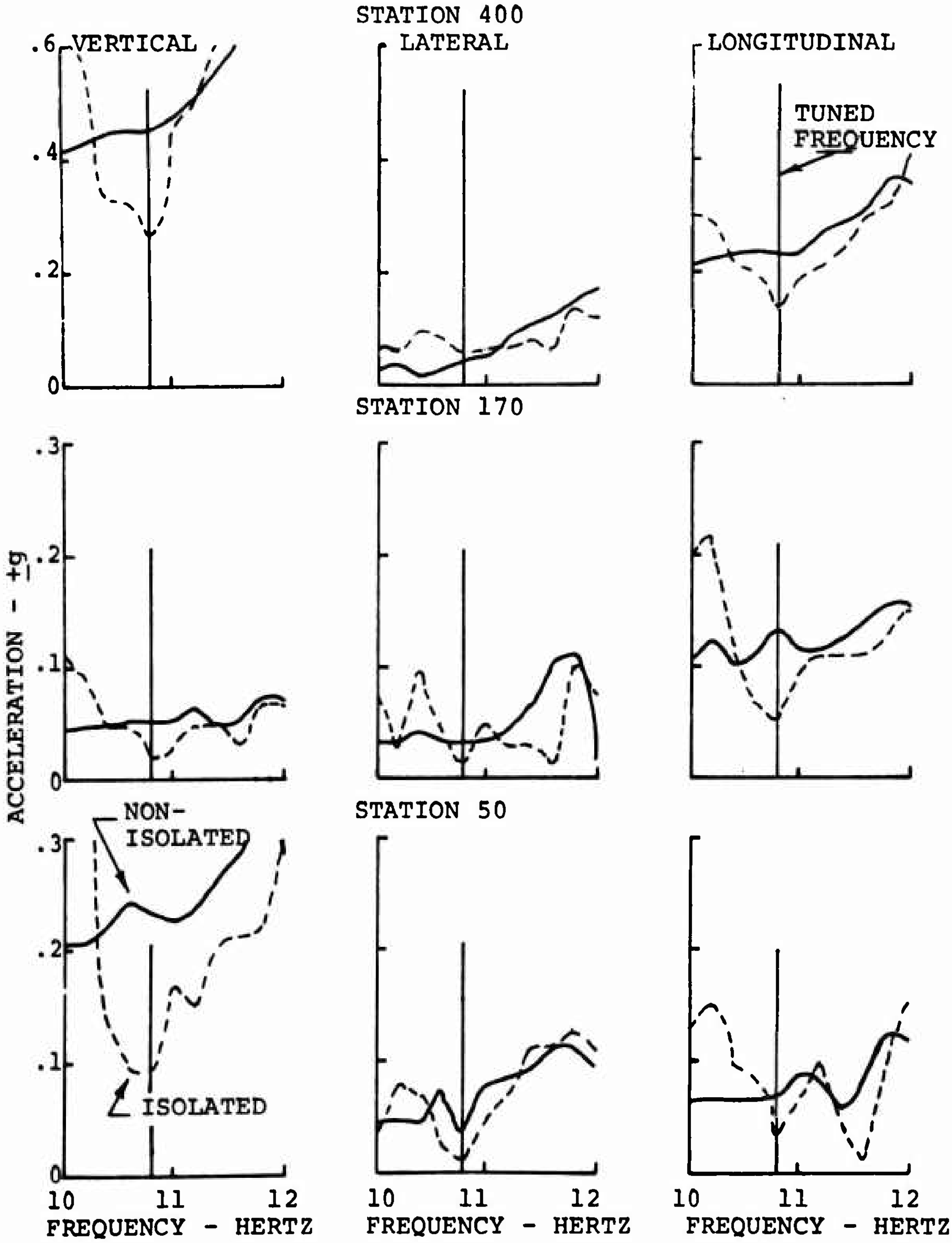


Figure 31. Responses of a Nonisolated and DAVI-Isolated Two-Bladed Helicopter for Longitudinal Excitation.

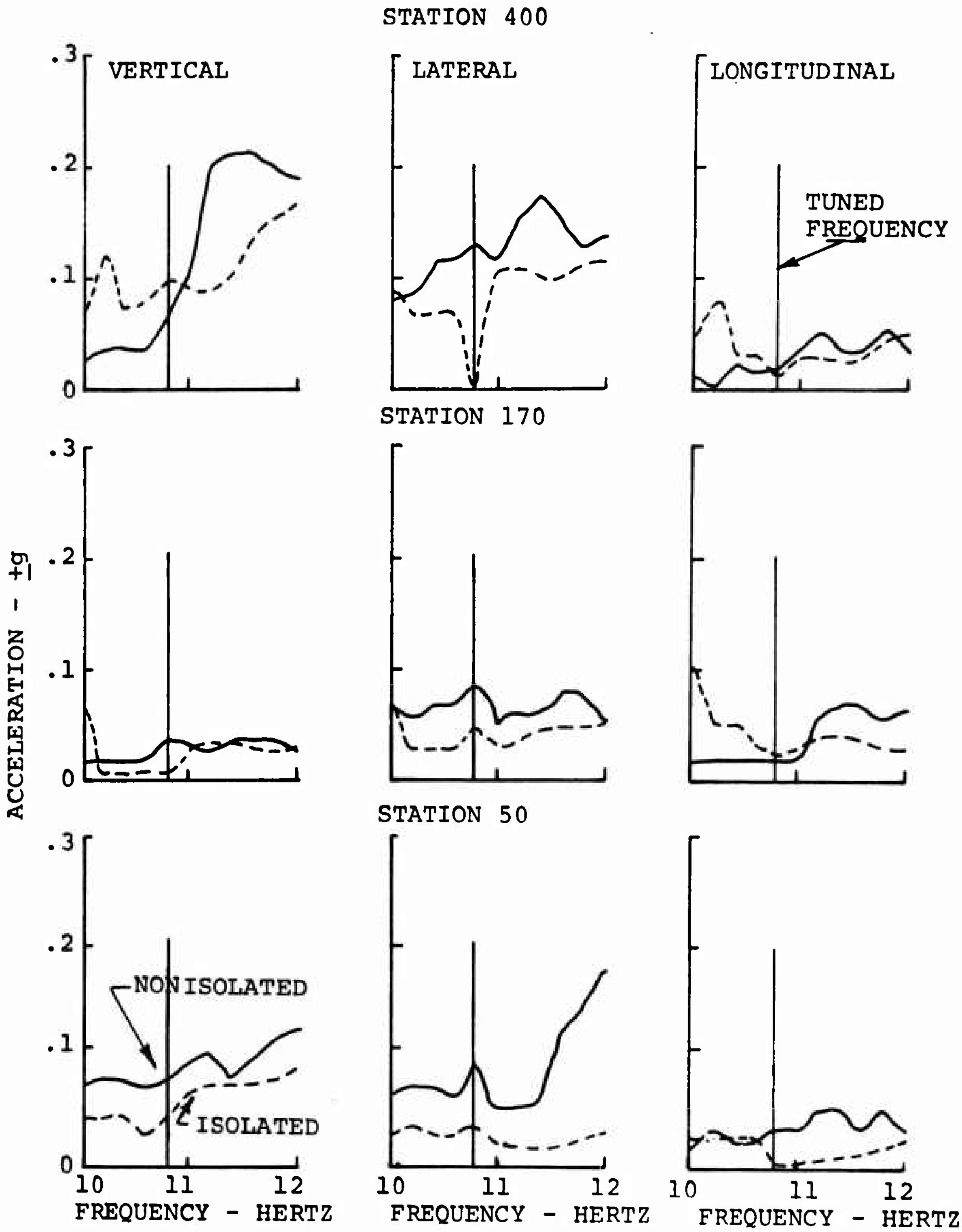


Figure 32. Responses of a Nonisolated and DAVI-Isolated Two-Bladed Helicopter for Lateral Excitation.

Figure 32 shows the results obtained for the lateral direction of excitation. It is seen from this figure that a decrease in vibration level was obtained in the lateral accelerations with the DAVI isolation system.

Figures 33, 34, and 35 show the effectivity of the DAVI isolation for a two-bladed helicopter. These figures show that good isolation was obtained at or near the antiresonant frequency of the DAVI isolation system. It is also seen that although the bandwidth of isolation is not as broad as obtained in the three- and four-bladed configurations, the bandwidth of isolation is definitely sufficient for helicopter applications.

Table XXII shows the results obtained for the one-per-rev, two-per-rev and four-per-rev frequencies, which would be the significant excitation frequencies of the two-bladed helicopter. These results are reported for shaking the helicopter with an excitation force of ±50 pounds at the one-per-rev frequency and with an excitation force of ±200 pounds at the four-per-rev excitation frequency.

It is seen from Table XXII that the response of the non-isolated helicopter at the two-per-rev excitation frequency was quite low for all directions of excitation. Even with this low response, isolation was achieved with the DAVI system. Where the response was relatively high, above ±.10 g, approximately 60-percent isolation was obtained. It is also shown that the one-per-rev levels are low and that the DAVI isolation system did not substantially affect the one-per-rev response.

Table XXIII shows the relative deflection obtained between the rotor and the fuselage for the three directions of excitation. The results are reported for shaking the helicopter with an excitation force of ±50 pounds at the one-per-rev frequency and with an excitation force of ±200 pounds at the four-per-rev frequency.

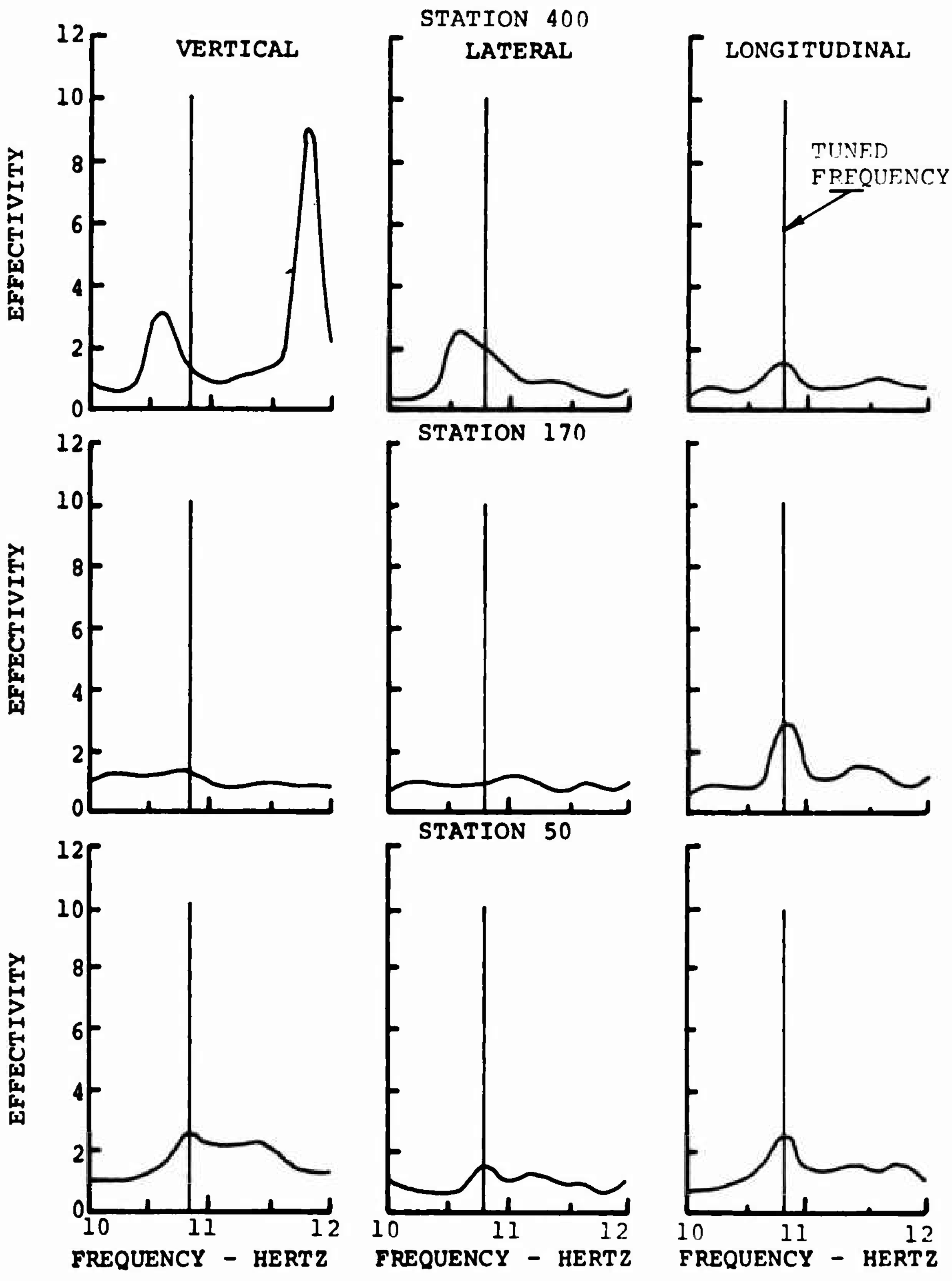


Figure 33. Effectivity of a DAVI-Isolated Two-Bladed Helicopter for Vertical Excitation.

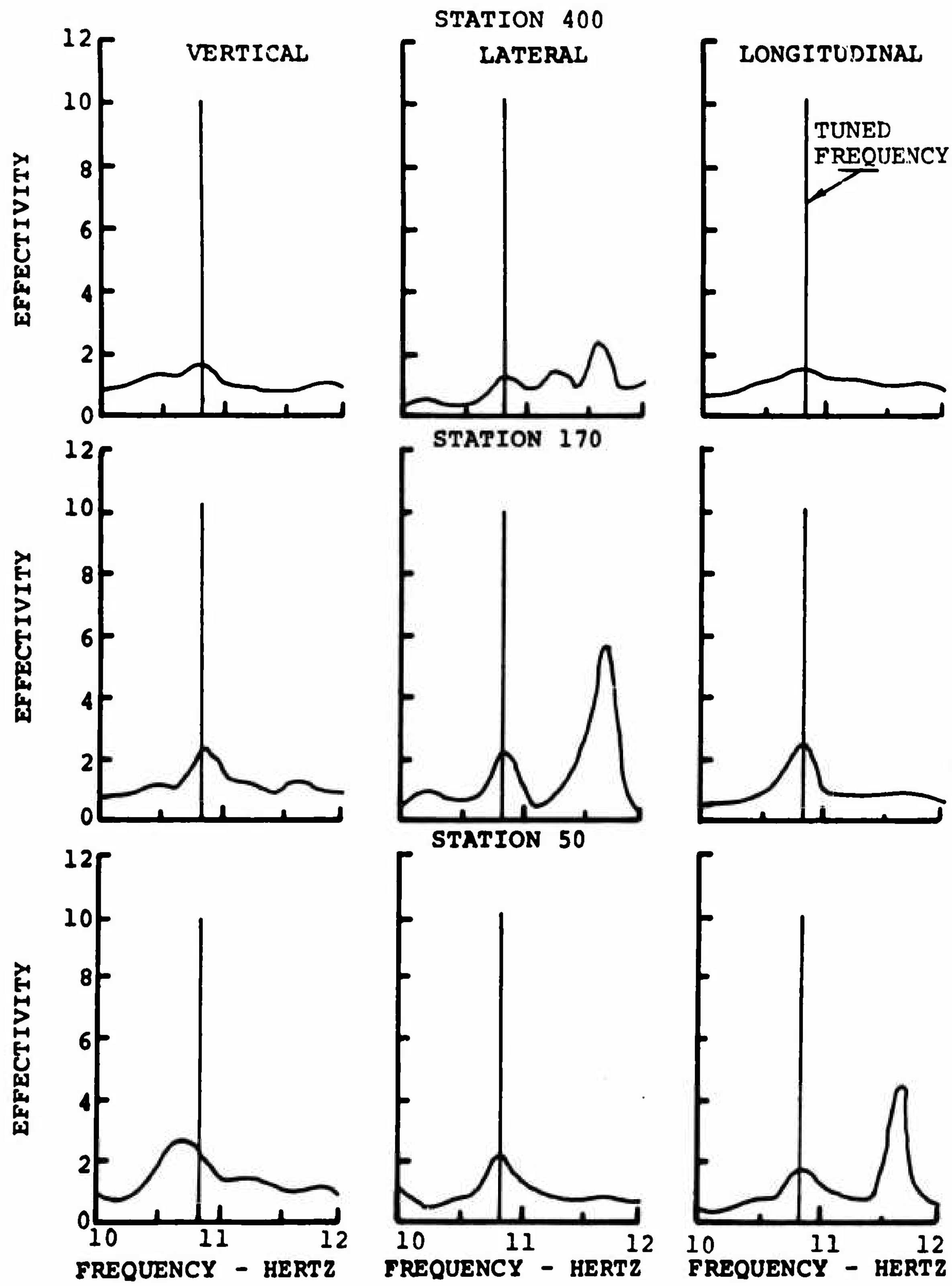


Figure 34. Effectivity of a DAVI-Isolated Two-Bladed Helicopter for Longitudinal Excitation.

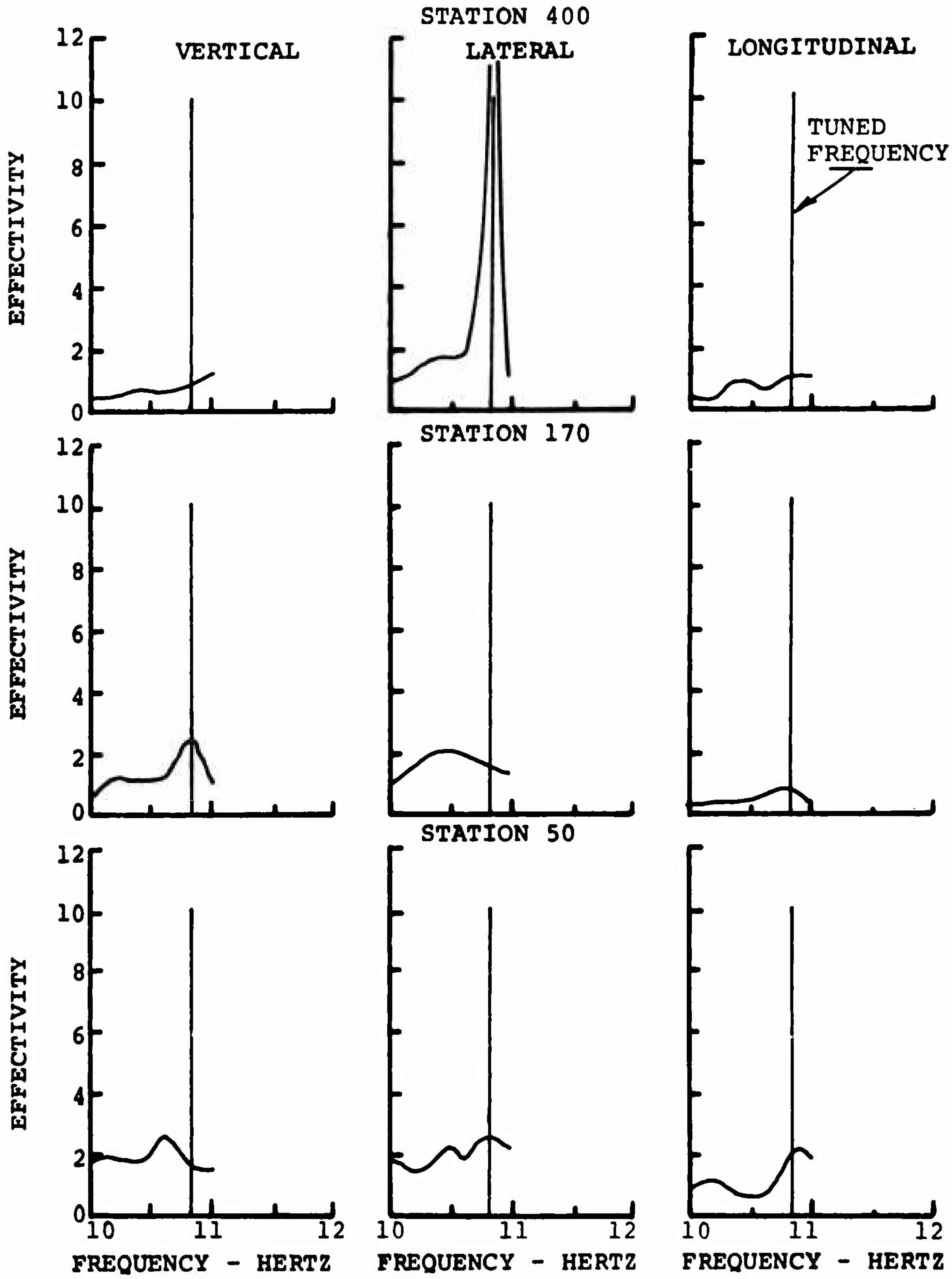


Figure 35 . Effectivity of a DAVI-Isolated Two-Bladed Helicopter for Lateral Excitation.

TABLE XXII. PREDOMINANT VIBRATION LEVELS OF THE TWO-BLADED HELICOPTER

Pickup Location		1-Per-Rev ($\pm g$)			2-Per-Rev ($\pm g$)			4-Per-Rev ($\pm g$)		
Sta	Direction	Non-Iso	Iso	T*	Non-Iso	Iso	T*	Non-Iso	Iso	T*
Vertical Excitation										
	Vert	.011	.010	.91	.050	.060	1.20	.494	.462	.94
400	Long.	.002	.002	1.00	.024	.017	.71	.204	.156	.75
	Lat	.006	.004	.67	.031	.024	.77	.073	.077	1.05
	Vert	.009	.010	1.11	.093	.065	.70	.144	.140	.97
170	Long.	.001	.002	2.00	.050	.017	.34	.009	.028	3.11
	Lat	.002	.002	1.00	.023	.033	1.43	.148	.184	1.24
	Vert	.009	.010	1.11	.152	.064	.42	.307	.251	.82
50	Long.	.001	.003	3.00	.055	.025	.46	.244	.041	.17
	Lat	.007	.002	.29	.050	.035	.71	.076	.159	2.09
Longitudinal Excitation										
	Vert	.016	.017	1.06	.450	.261	.58	.431	.400	.93
400	Long.	.015	.014	.93	.230	.136	.59	.246	.234	.95
	Lat	.007	.002	.29	.044	.034	.77	.070	.040	.57
	Vert	.003	.002	.67	.051	.025	.49	.013	.052	4.00
170	Long.	.010	.010	1.00	.133	.053	.40	.146	.169	1.16
	Lat	.003	.003	1.00	.036	.017	.47	.071	.081	1.13
	Vert	.014	.014	1.00	.235	.097	.41	.358	.166	.46
50	Long.	.009	.007	.78	.070	.035	.50	.228	.198	.87
	Lat	.004	.002	.50	.038	.018	.47	-	.073	-
Lateral Excitation										
	Vert	.006	.002	.33	.079	.108	1.36	.214	.346	1.62
400	Long.	.004	.005	1.25	.017	.017	1.00	.062	.141	2.27
	Lat	.008	.010	1.25	.131	.008	.06	.024	.049	2.04
	Vert	.002	.002	1.00	.034	.016	.47	.082	.156	1.90
170	Long.	.002	.002	1.00	.018	.026	1.44	.190	.136	.72
	Lat	.004	.005	1.25	.086	.050	.58	.229	.198	.86
	Vert	.005	.003	.60	.083	.047	.57	.098	.154	1.57
50	Long.	.003	.003	1.00	.035	.017	.49	.188	.166	.88
	Lat	.003	.002	.67	.102	.044	.43	.220	.126	.57

*T = Transmissibility; ratio isolated/nonisolated response.

TABLE XXIII. RELATIVE DEFLECTION IN THE DAVI ISOLATION SYSTEM FOR A TWO-BLADED HELICOPTER

DAVI Location	Direction	Relative Deflection ($\pm$in.) 1-Per-Rev	2-Per-Rev	4-Per-Rev
Vertical Excitation				
Left Fwd	Vertical	.0005	.0171	.0022
	Longitudinal	-	.0002	-
	Lateral	-	.0014	.0001
Rt Fwd	Vertical	.0005	.0094	.0021
	Longitudinal	-	.0016	.0001
	Lateral	-	.0002	.0003
Rt Aft	Vertical	.0005	.0212	.0018
	Longitudinal	-	.0006	-
	Lateral	-	.0011	.0005
Left Aft	Vertical	.0006	.0040	.0028
	Longitudinal	.0001	.0015	.0004
	Lateral	-	.0002	.0004
Longitudinal Excitation				
Left Fwd	Vertical	.0004	.0125	.0008
	Longitudinal	.0002	.0003	.0003
	Lateral	-	.0029	-
Rt Fwd	Vertical	.0002	.0320	.0005
	Longitudinal	.0003	.0044	.0008
	Lateral	-	.0045	.0003
Rt Aft	Vertical	.0003	.0264	.0003
	Longitudinal	.0002	.0031	.0007
	Lateral	-	.0036	-
Left Aft	Vertical	.0003	.0026	.0013
	Longitudinal	.0003	.0030	.0011
	Lateral	-	.0007	.0001

TABLE XXIII - Continued				
Lateral Excitation				
DAVI Location	Direction	Relative Deflection ($\pm$in.)		
		1-Per-Rev	2-Per-Rev	4-Per-Rev
Left Fwd	Vertical	.0005	.0081	.0079
	Longitudinal	-	.0002	.0007
	Lateral	.0001	.0020	.0004
Rt Fwd	Vertical	.0004	.0069	.0039
	Longitudinal	-	.0010	.0004
	Lateral	.0002	.0065	.0009
Rt Aft	Vertical	.0003	.0036	.0042
	Longitudinal	-	.0004	.0003
	Lateral	.0002	.0052	.0002
Left Aft	Vertical	.0004	.0034	.0072
	Longitudinal	.0001	.0014	.0010
	Lateral	.0002	.0015	.0007

This table shows the relative deflection to be small. The greatest deflection occurred at the two-per-rev excitation frequency, and the primary deflection occurred in the vertical direction of the mounts. The small vertical deflections that were obtained for the longitudinal and lateral directions of excitation indicated a minimum of relative rotation between the upper and lower bodies. These small angular and translation deflections should present no problems to coupling or shafting between the engine and transmission.

Exploratory Testing

As anticipated from the analysis and confirmed from the testing of the three basic rotor configurations, the two-bladed 6500-pound configuration was the most difficult to isolate because this configuration has a very low n-per-rev frequency and close proximity of the one-per-rev frequency, system natural frequencies, and n-per-rev frequency. In order to determine the effects of various DAVI parameters and structural changes on the vibration level of the test vehicle, several modifications were made and exploratory testing was done at and near the two-per-rev excitation frequency. The purpose of this testing was to assist in determining parameters for future DAVI designs.

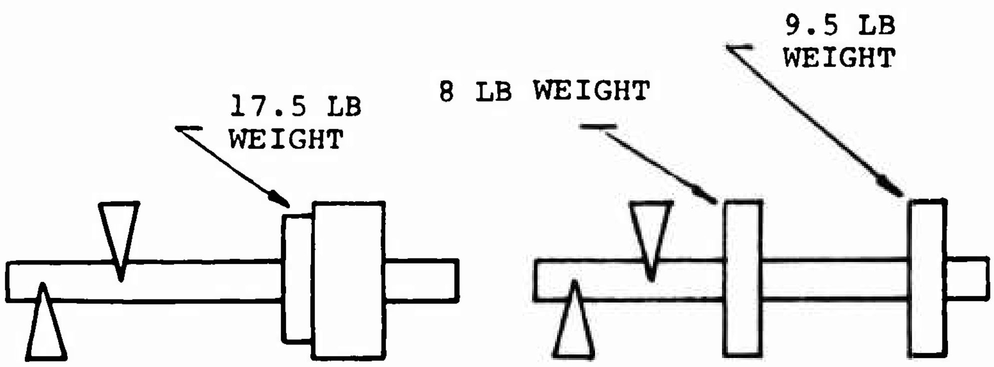
One obvious modification to the system would be a change in pivots to either antifriction bearings or flexural pivots to reduce damping and therefore obtain lower vibration levels; this modification was not in the scope of the present program. However, modifications were made changing the moment of inertia and weight of the inertia bar, and reducing the static deflection. Table XXIV shows the modifications made and the exploratory tests conducted.

Configuration 1 was tested to determine the effects of increased inertia of the unidirectional inertia bar on the vibration characteristics of the DAVI isolation system. The antiresonant frequency of the DAVI is

$$\omega_A{}^2 = \frac{K_D}{M_D[(\frac{R}{r})(\frac{R}{r} - 1) + \rho^2/r^2]} \qquad (1)$$

The same antiresonant frequency can be maintained by reducing R/r and increasing ρ^2/r^2 or the inertia of the bar. This increased inertia also has the effect of decreasing the natural frequency. This increase in inertia was accomplished by split weights as shown in Figure 36.

TABLE XXIV. EXPLORATORY TEST CONFIGURATIONS		
Configuration Number	Configuration	Direction of Excitation
1	Increased inertia of unidirectional inertia bar	Vertical Longitudinal Lateral
2	Three-DAVI configuration	Vertical Longitudinal Lateral
3	Three-DAVI configuration with no in-plane inertia bar weights	Longitudinal
4	Three-DAVI configuration with in-plane inertia bar weights and increased unidirectional inertia bar weight	Vertical Longitudinal
5	Three-DAVI configuration (No. 4) with reduced upper body structural stiffening	Vertical Longitudinal



(a) Single Weight (b) Split Weight

Figure 36. Unidirectional Inertia Bar.

Figures 37, 38, and 39 show the results obtained with this modification. It is seen from these figures that the results obtained were not as good as previously obtained with the original two-bladed rotor configuration (Figures 30, 31, and 32). The resulting vibration levels were higher and the anti-resonant frequency was less pronounced.

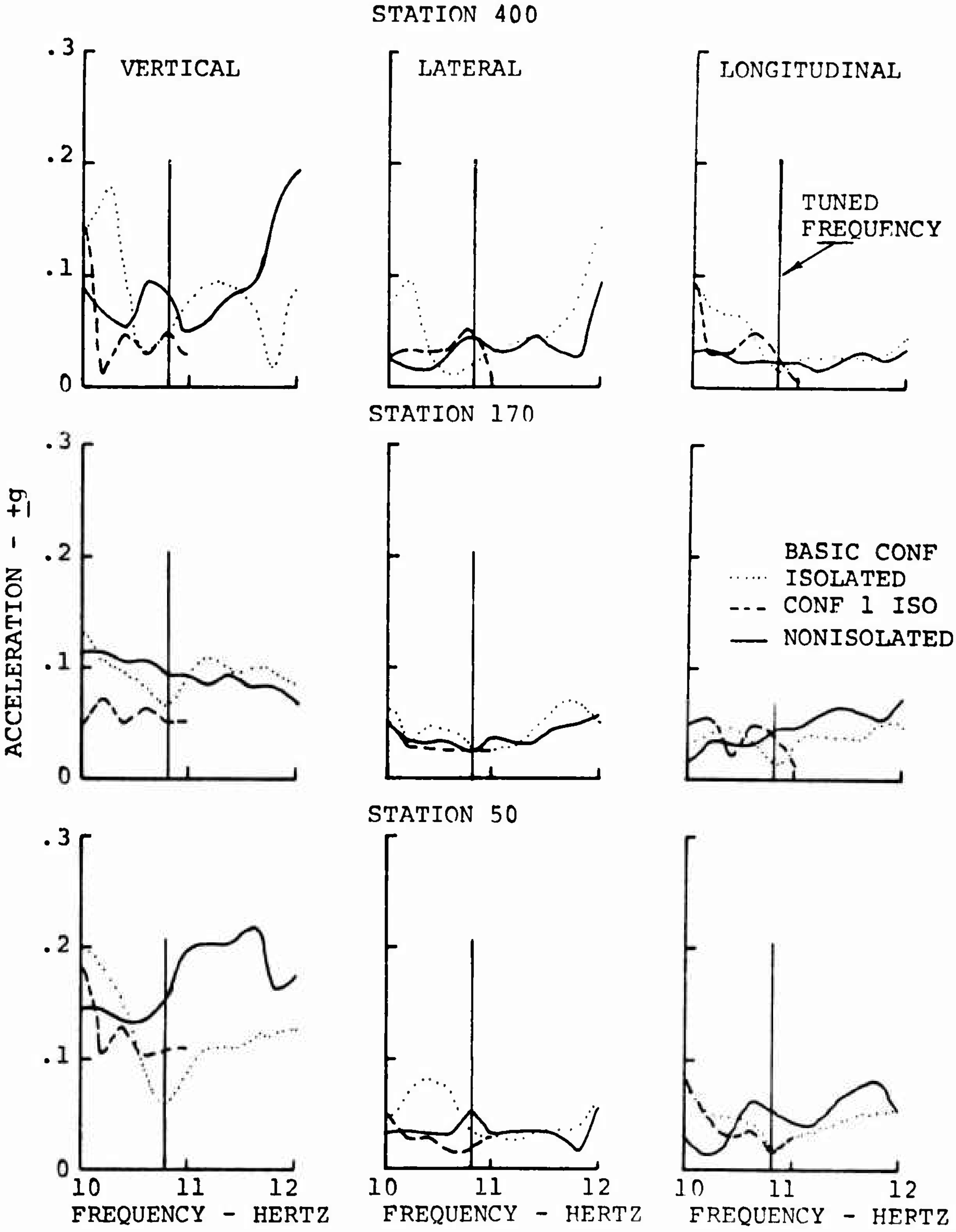


Figure 37. Response of an Isolated Two-Bladed Helicopter With Increased Inertia of the Unidirectional DAVI Inertia Bar for Vertical Excitation.

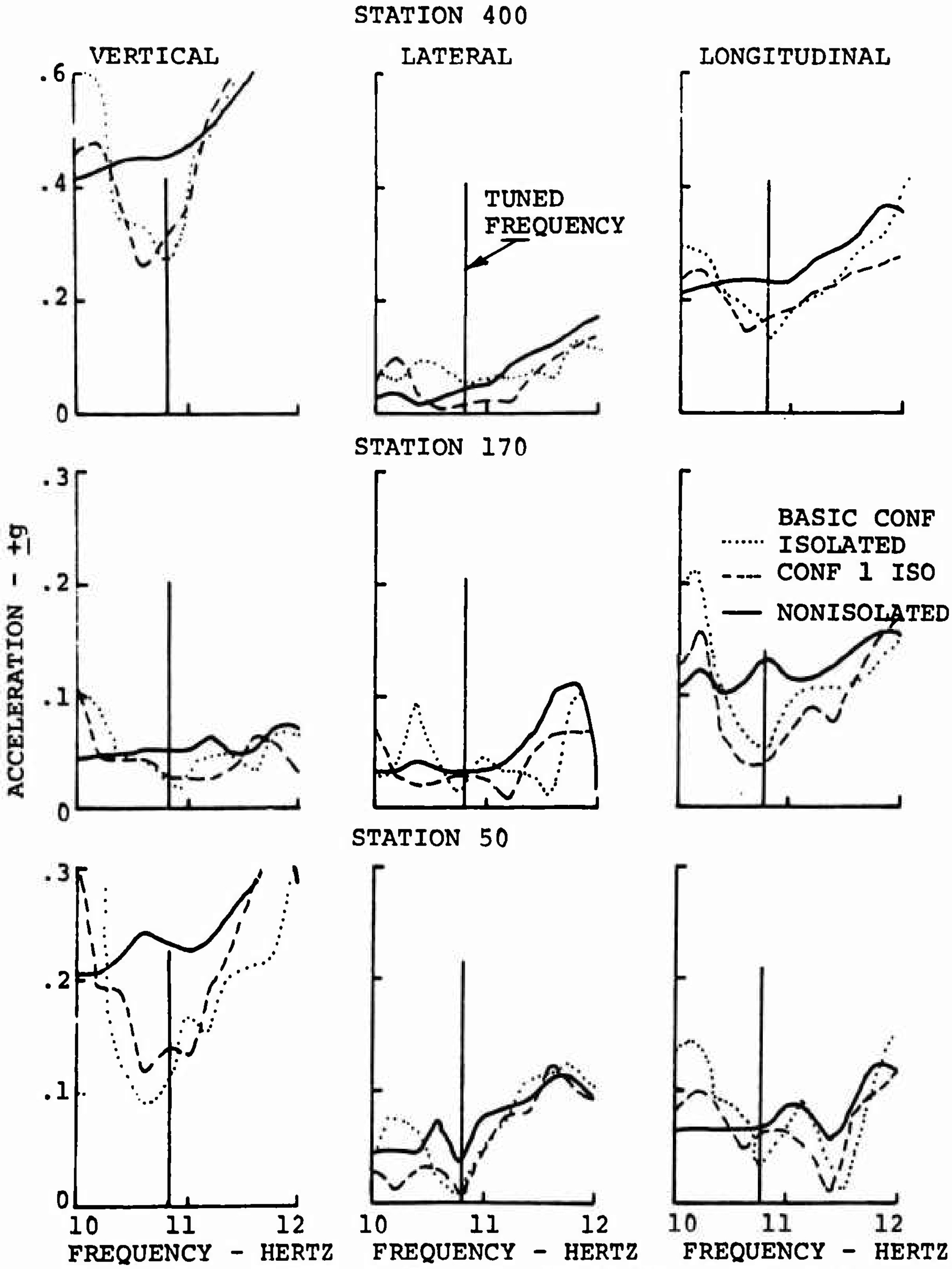


Figure 38. Response of an Isolated Two-Bladed Helicopter With Increased Inertia of the Unidirectional DAVI Inertia Bar for Longitudinal Excitation.

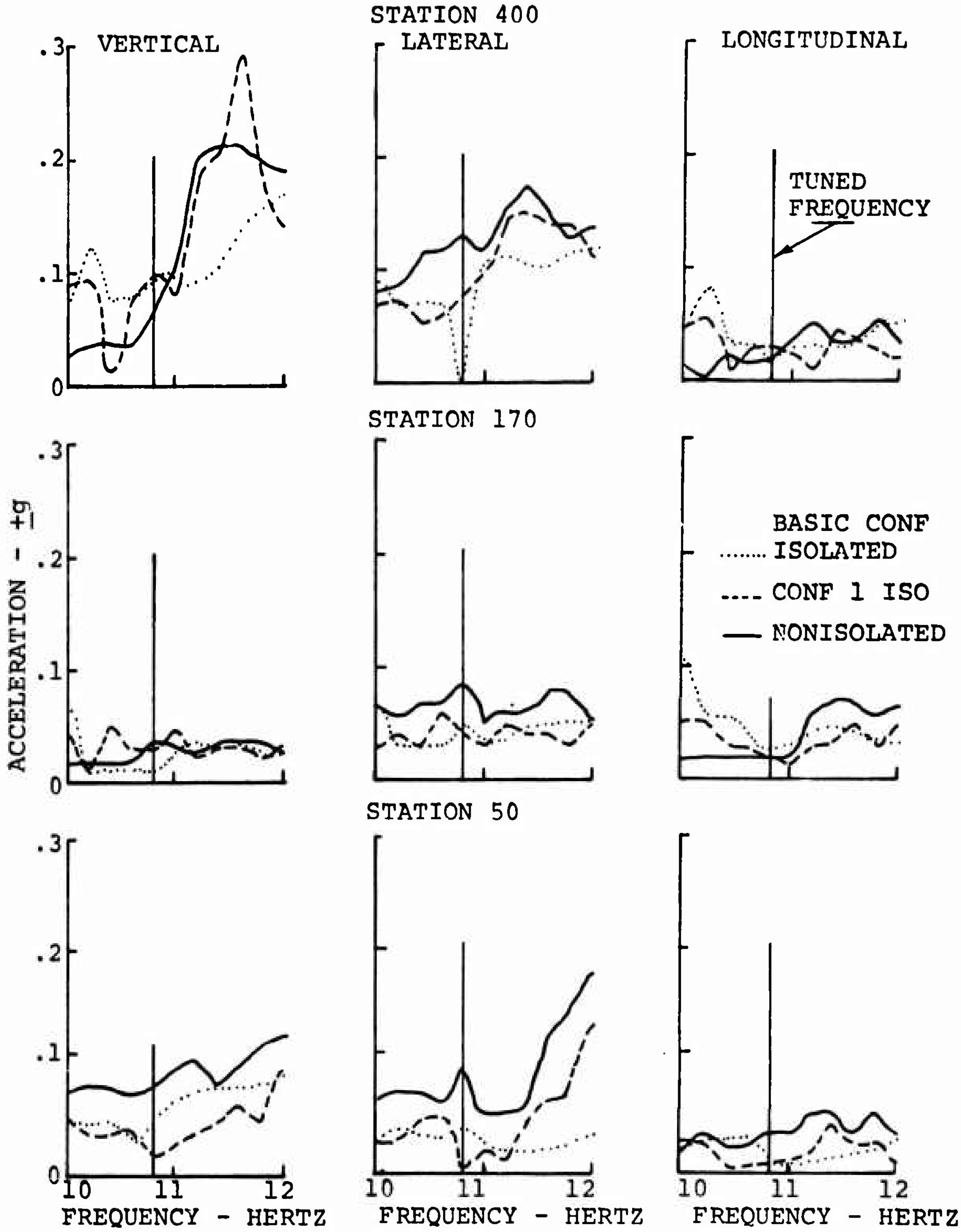


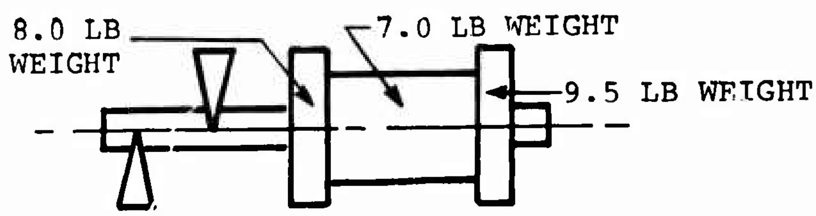
Figure 39. Response of an Isolated Two-Bladed Helicopter With Increased Inertia of the Unidirectional DAVI Inertia Bar for Lateral Excitation.

The three-DAVI configuration (Configuration 2) was accomplished by removing the aft rear DAVI as shown in Figure 40. This three-DAVI configuration is not symmetrical, but does satisfy the main purpose of this test, which was to determine the effects of an overall reduced system spring rate.

Figures 41, 42, and 43 show the results of this modification. There was no significant change in the vibrational level when compared to the original two-bladed rotor configuration (Figures 30, 31, and 32). There was a slight improvement in the vertical acceleration at Station 50 for the vertical direction of excitation, and all three transducer locations had a broader bandwidth of isolation in the longitudinal direction for the longitudinal direction of excitation.

Figure 44 shows the results obtained from the test of Configuration 3 in which the movable weights on the two-dimensional inertia bar were removed. This test simulated a DAVI isolation system in the vertical direction with conventional isolation in the in-plane directions. This test was conducted for only the longitudinal direction of excitation. It is seen from this figure that a reduction of vibration was obtained. However, the bandwidth at station 50 in the vertical direction was very narrow.

The three-DAVI configuration with increased unidirectional inertia bar weight was tested. The increased unidirectional inertia bar weight is shown in the following schematic.



This configuration was tested for vertical and longitudinal directions of excitation. Figures 45 and 46 show the results of these tests. It is seen from Figure 45 that very good reduction in vibration was obtained at stations 50 and 170 and that a broad bandwidth of isolation was achieved. It is seen in Figure 46 that a good reduction in vibration was also obtained.

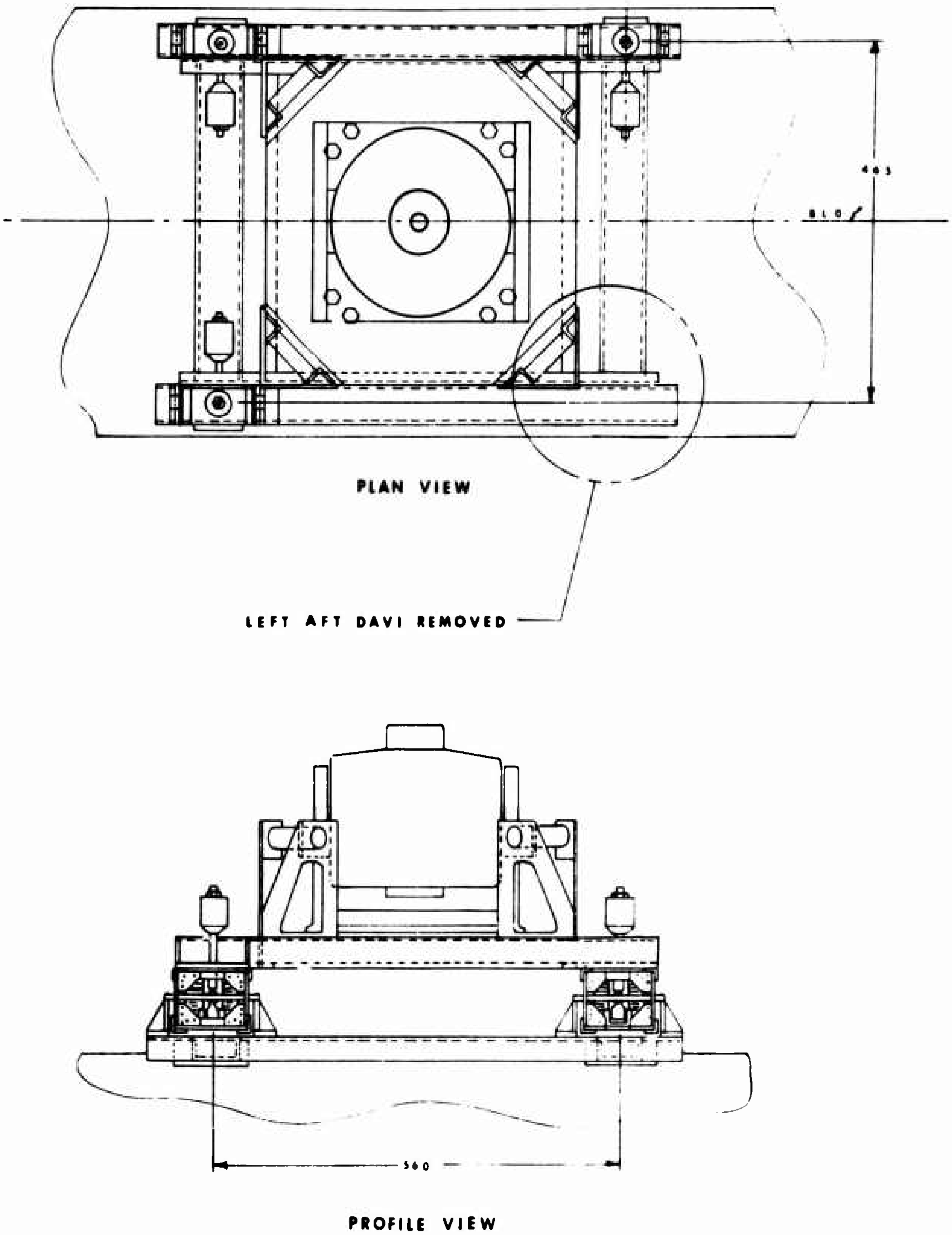


Figure 40. Three-DAVI Configuration.

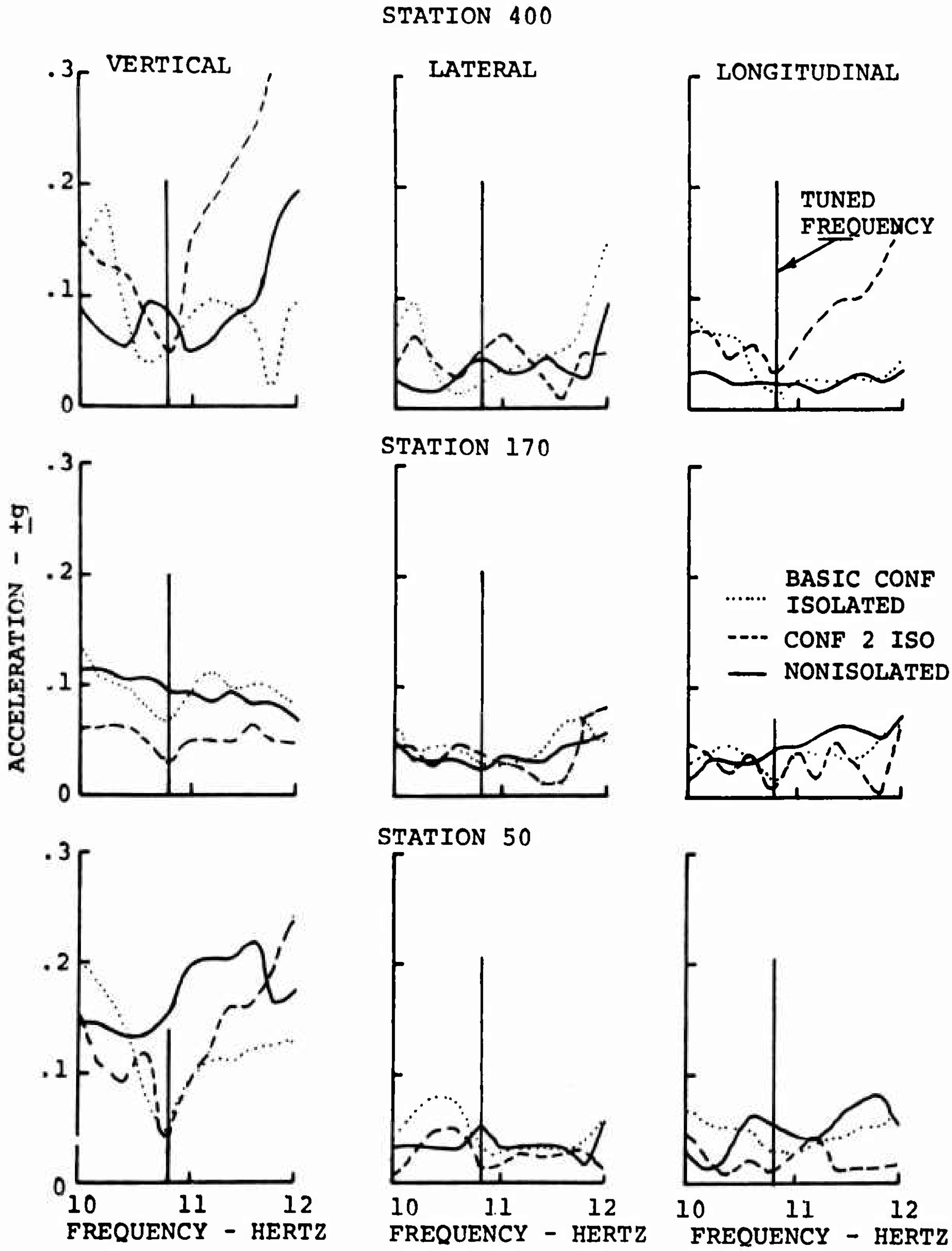


Figure 41. Response of an Isolated Two-Bladed Helicopter With a Three-DAVI Configuration for Vertical Excitation.

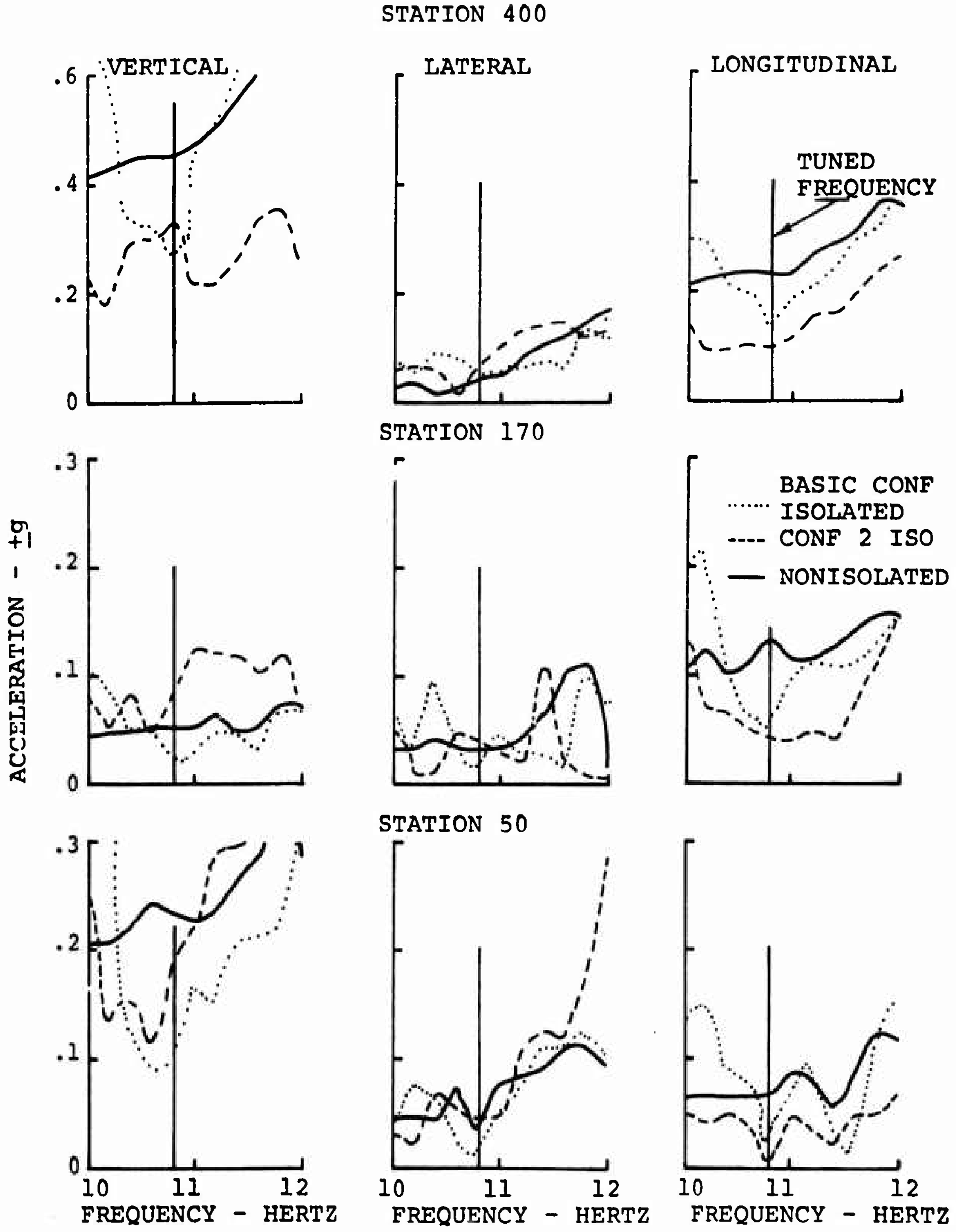


Figure 42. Response of an Isolated Two-Bladed Helicopter With a Three-DAVI Configuration for Longitudinal Excitation.

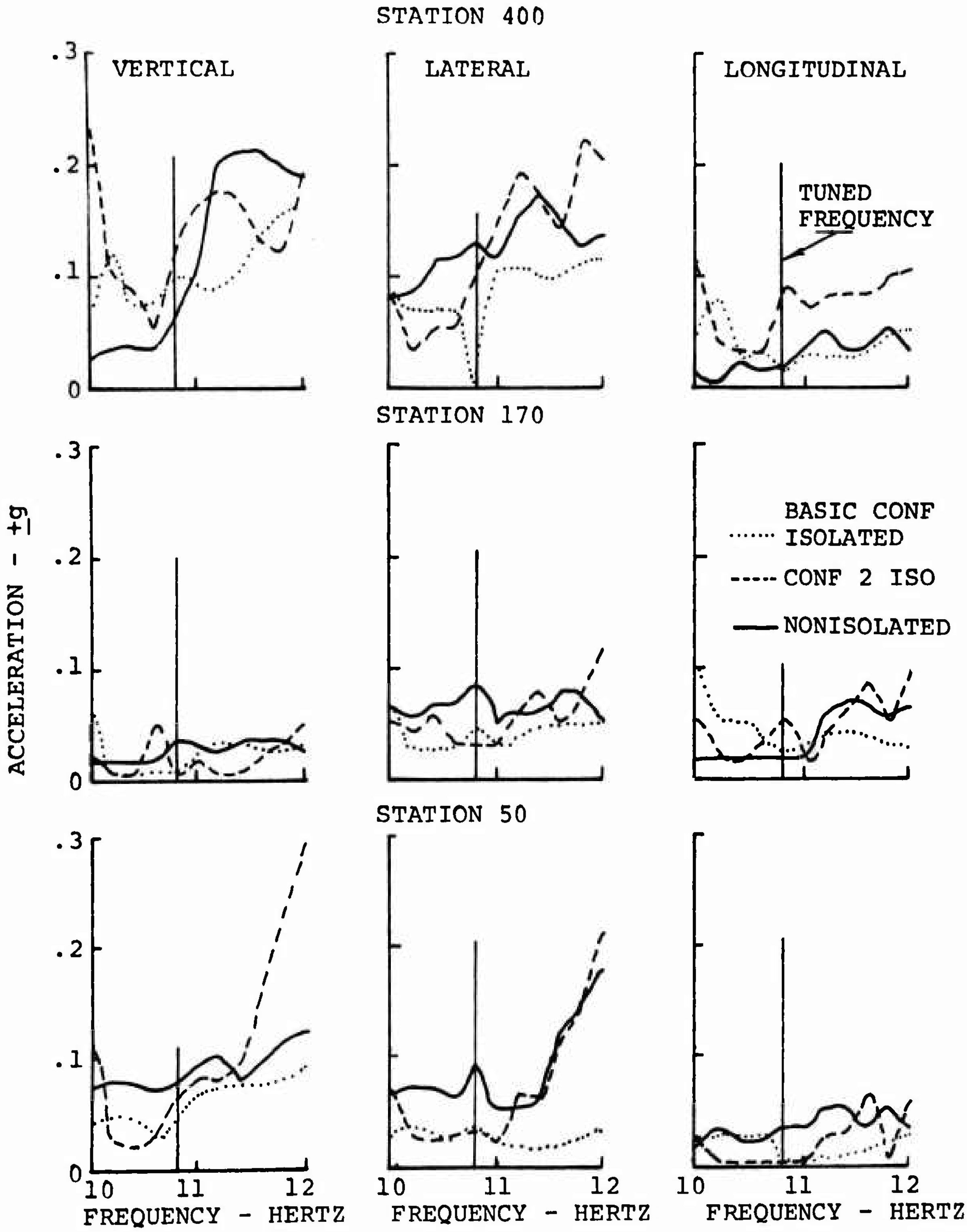


Figure 43. Response of an Isolated Two-Bladed Helicopter With a Three-DAVI Configuration for Lateral Excitation.

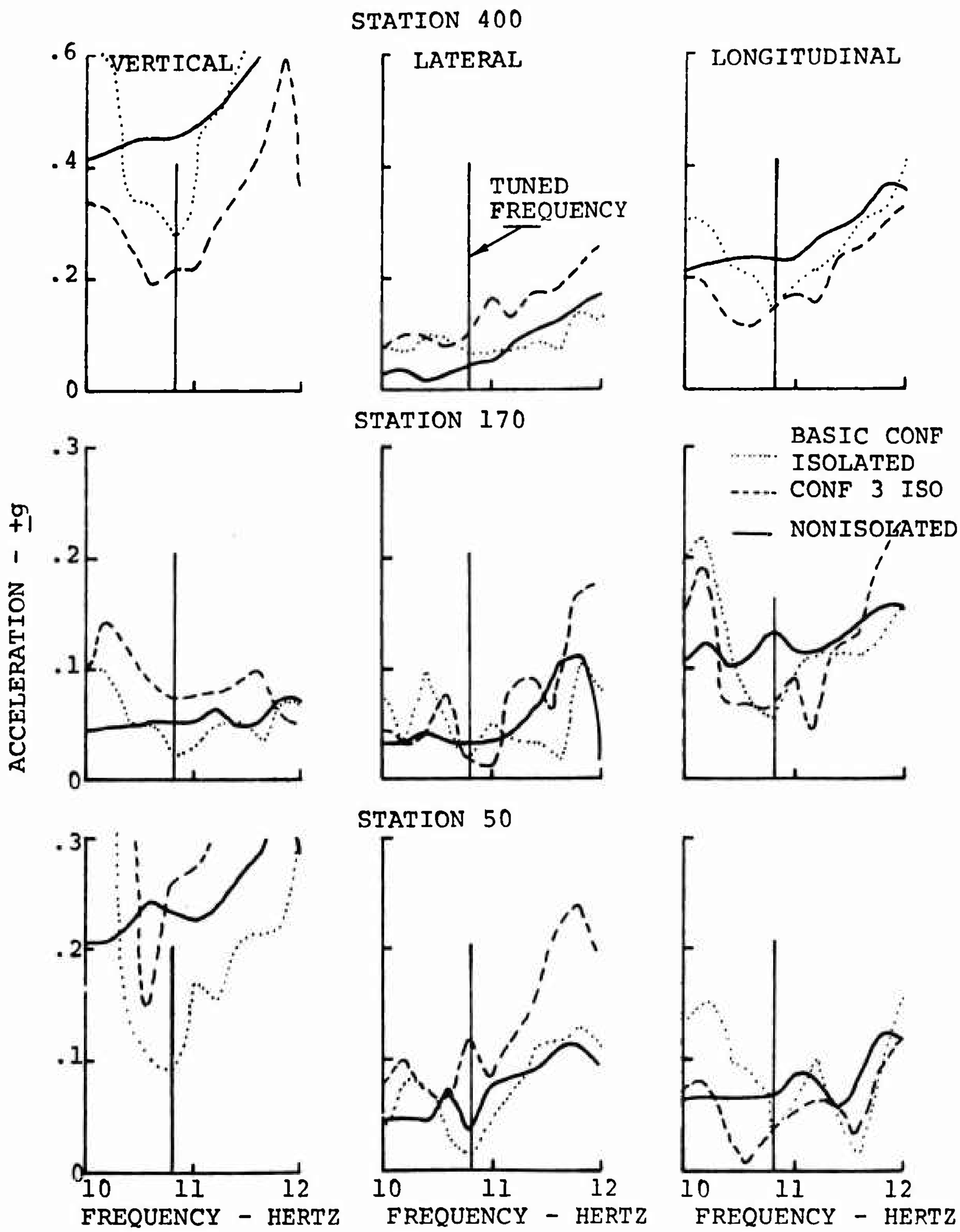


Figure 44. Response of an Isolated Two-Bladed Helicopter With a Three-DAVI Configuration and No In-Plane Weights on Inertia Bar for Longitudinal Excitation.

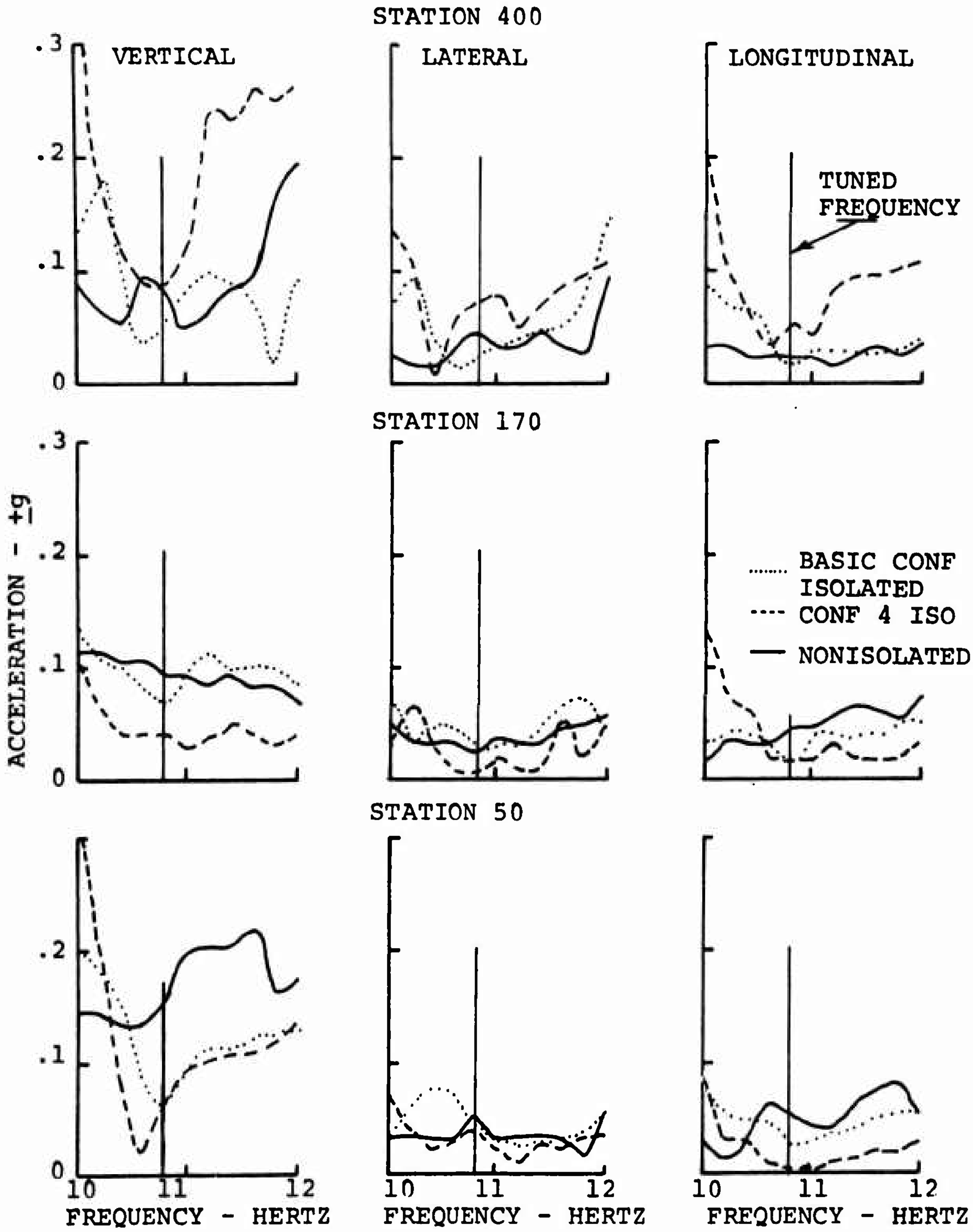


Figure 45. Response of an Isolated Two-Bladed Helicopter With a Three-DAVI Configuration and Increased Unidirectional Inertia Bar Weight for Vertical Excitation.

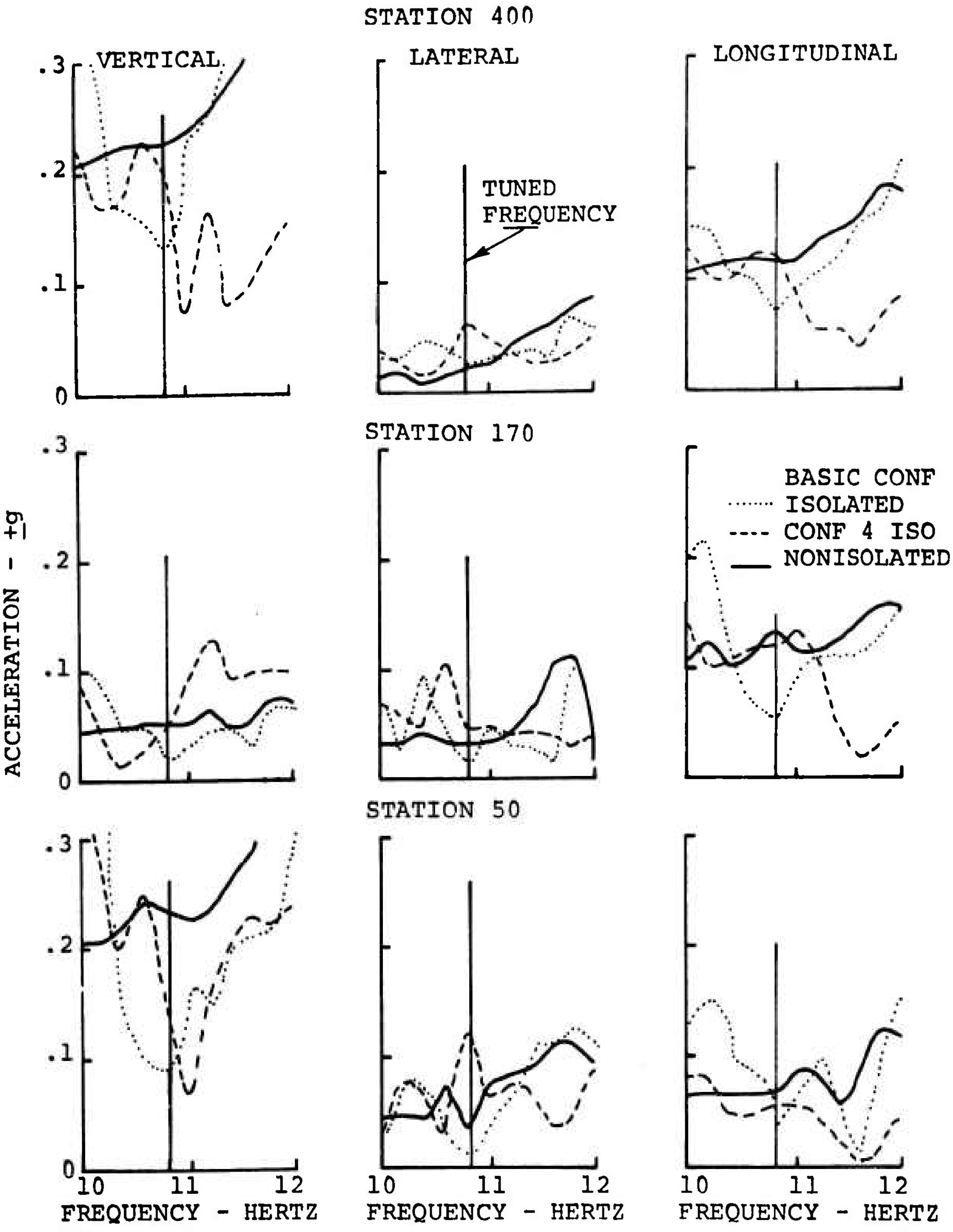


Figure 46. Response of an Isolated Two-Bladed Helicopter With a Three-DAVI Configuration and Increased Unidirectional Inertia Bar Weight for Longitudinal Excitation.

The three-DAVI configuration with reduced structural stiffening of the upper body was tested. This reduced stiffness was accomplished by removing the angle stiffening that was shown in Figure 17. Figures 47 and 48 show the results of these tests. These figures show, in most cases, a good reduction in vibration level. There is a slight discrepancy in the antiresonance obtained in the vertical direction of excitation as compared to the antiresonant frequency obtained in the longitudinal direction.

Table XXV gives a summary of the results obtained for all of the exploratory testing done. It is seen from this testing that none of the modifications made any significant difference in the vibration level as compared to the basic configuration. All of the configurations, in most cases, had a lower vibration level than the nonisolated helicopter. It was anticipated that the reduced spring rate would give lower vibration levels than the basic isolated case; however, the exploratory test results did not confirm this. In order to obtain a better comparison between the basic isolated case and the nonisolated helicopter, a complete vibration survey was made on Configuration 5.

Three-DAVI Configuration

A complete vibration survey from 5 Hertz to 25 Hertz for all three directions of excitation was made for the three-DAVI configuration (Configuration 5 of Table XXIV). Preliminary testing was done to achieve the proper antiresonance at 10.8 Hertz, which is the predominant excitation frequency of the two-bladed helicopter. Because of this tuning, these configuration results will differ from those reported earlier. This resulted in the following characteristics of the DAVI isolation system as shown in Table XXVI.

Figures 49, 50, and 51 show the results obtained for the nonisolated and DAVI-isolated two-bladed helicopter. It is seen from these results that for all directions of excitation, a reduction of vibration level was obtained with the DAVI isolation system.

Figures 52, 53, and 54 show the effectivity of the DAVI isolation system for a two-bladed helicopter. These figures show that good isolation was obtained at or near the antiresonant frequency. In comparing these results to the results obtained on the original two-bladed rotor configuration (Figures 33, 34, and 35), it is seen that greater effectivity was obtained for the three-DAVI isolation system than for the four-DAVI isolation system for the vertical direction of excitation. For the longitudinal and lateral directions of excitation, the results were about the same.

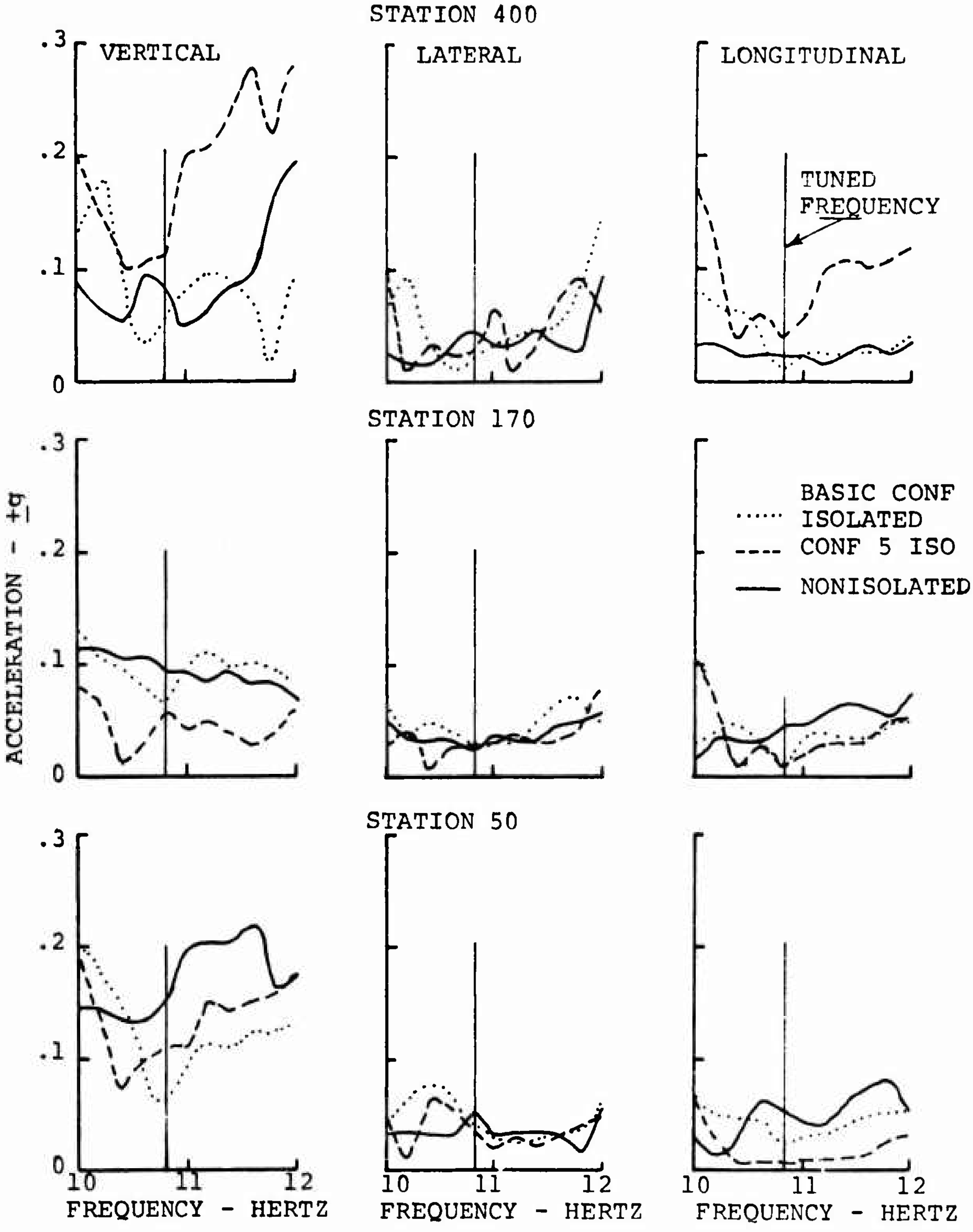


Figure 47. Response of an Isolated Two-Bladed Helicopter With a Three-DAVI Configuration and Reduced Structural Stiffness for Vertical Excitation.

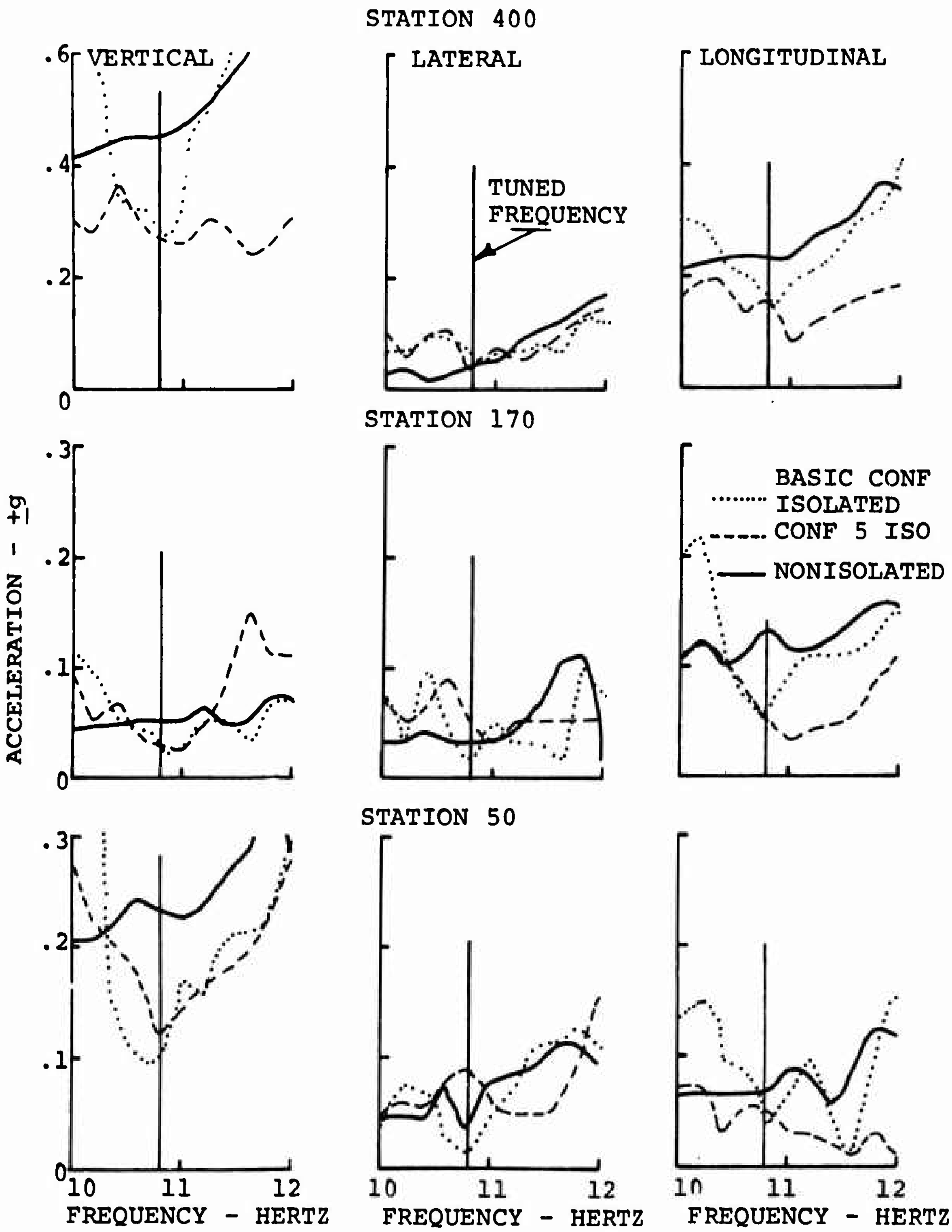


Figure 48. Response of an Isolated Two-Bladed Helicopter With a Three-DAVI Configuration and Reduced Structural Stiffness for Longitudinal Excitation.

TABLE XXV. RESPONSES OF TWO-BLADED HELICOPTER AT PREDOMINANT ROTOR EXCITATION FREQUENCY - 2/REV

Configuration	Station 50 Vert	Station 50 Long.	Station 50 Lat	Station 170 Vert	Station 170 Long.	Station 170 Lat	Station 400 Vert	Station 400 Long	Station 400 Lat.
	Acceleration (±g)								
Vertical Excitation									
Nonisolated	.152	.055	.050	.093	.050	.023	.050	.024	.031
Isolated Conf									
Basic	.064	.025	.035	.065	.017	.033	.060	.017	.024
1	.106	.017	.030	.061	.045	.034	.034	.017	.034
2	.056	.017	.018	.033	.018	.033	.060	.034	.054
3	Not Tested			Not Tested			Not Tested		
4	.064	.008	.045	.040	.018	.008	.085	.051	.062
5	.095	.008	.040	.033	.009	.030	.100	.051	.024
Longitudinal Excitation									
Nonisolated	.235	.070	.038	.051	.133	.036	.450	.230	.044
Isolated Conf									
Basic	.097	.035	.018	.025	.053	.017	.261	.136	.034
1	.130	.051	.017	.032	.043	.024	.269	.150	.017
2	.120	.018	.058	.052	.047	.047	.210	.110	.017
3	.146	.010	.069	.079	.067	.068	.195	.127	.080
4	.120	.064	.115	.051	.115	.043	.400	.230	.140
5	.119	.050	.085	.034	.054	.054	.272	.150	.036
Lateral Excitation									
Nonisolated	.083	.035	.102	.034	.018	.086	.079	.017	.131
Isolated Conf									
Basic	.047	.017	.044	.016	.026	.050	.108	.017	.008
1	.0247	.017	.018	.016	.018	.034	.052	.034	.052
2	.025	.016	.010	.045	.034	.034	.052	.034	.052
3	Not Tested			Not Tested			Not Tested		
4	Not Tested			Not Tested			Not Tested		
5	Not Tested			Not Tested			Not Tested		

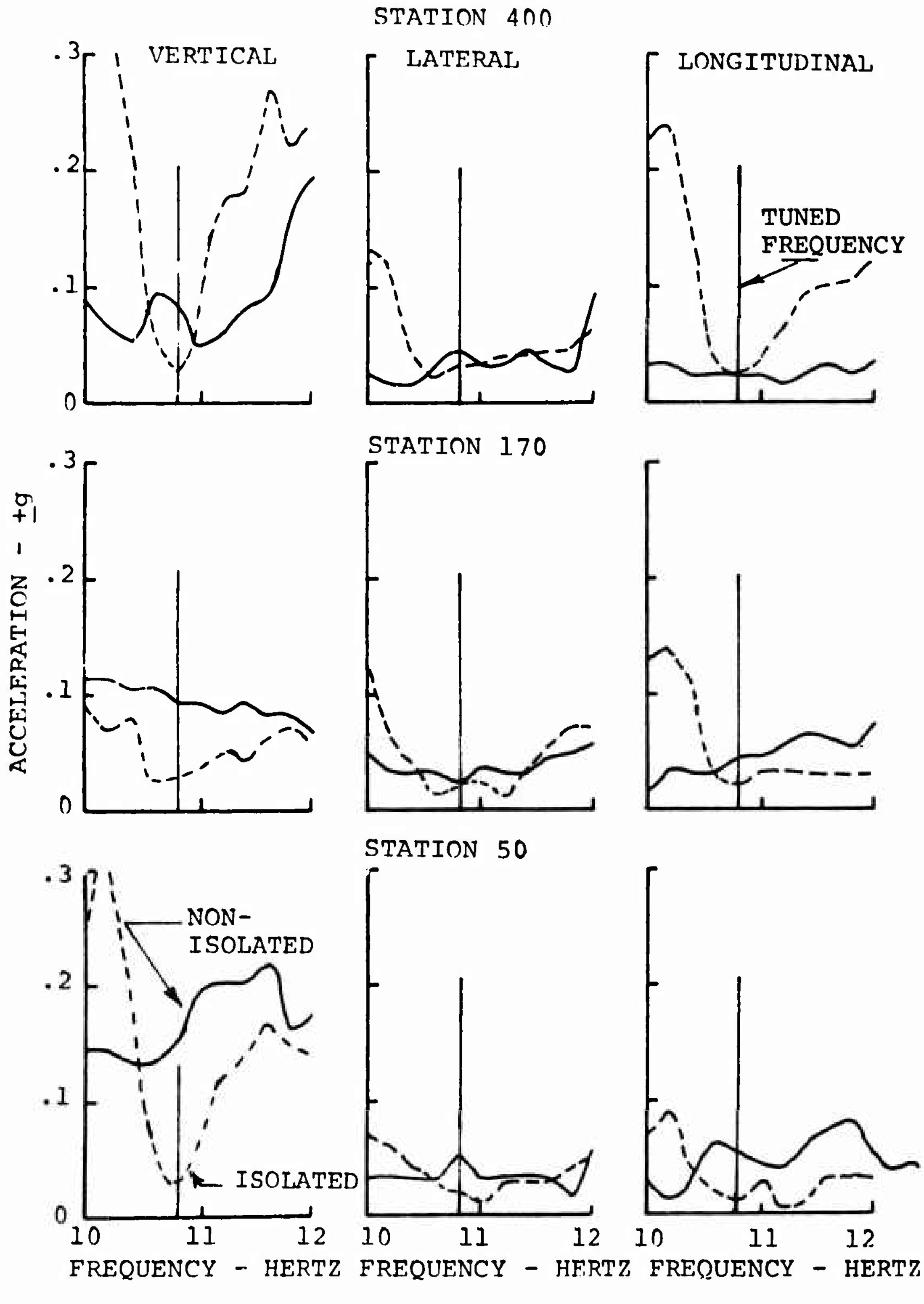


Figure 49. Responses of a Nonisolated and Three-DAVI-Isolated Two-Bladed Helicopter for Vertical Excitation.

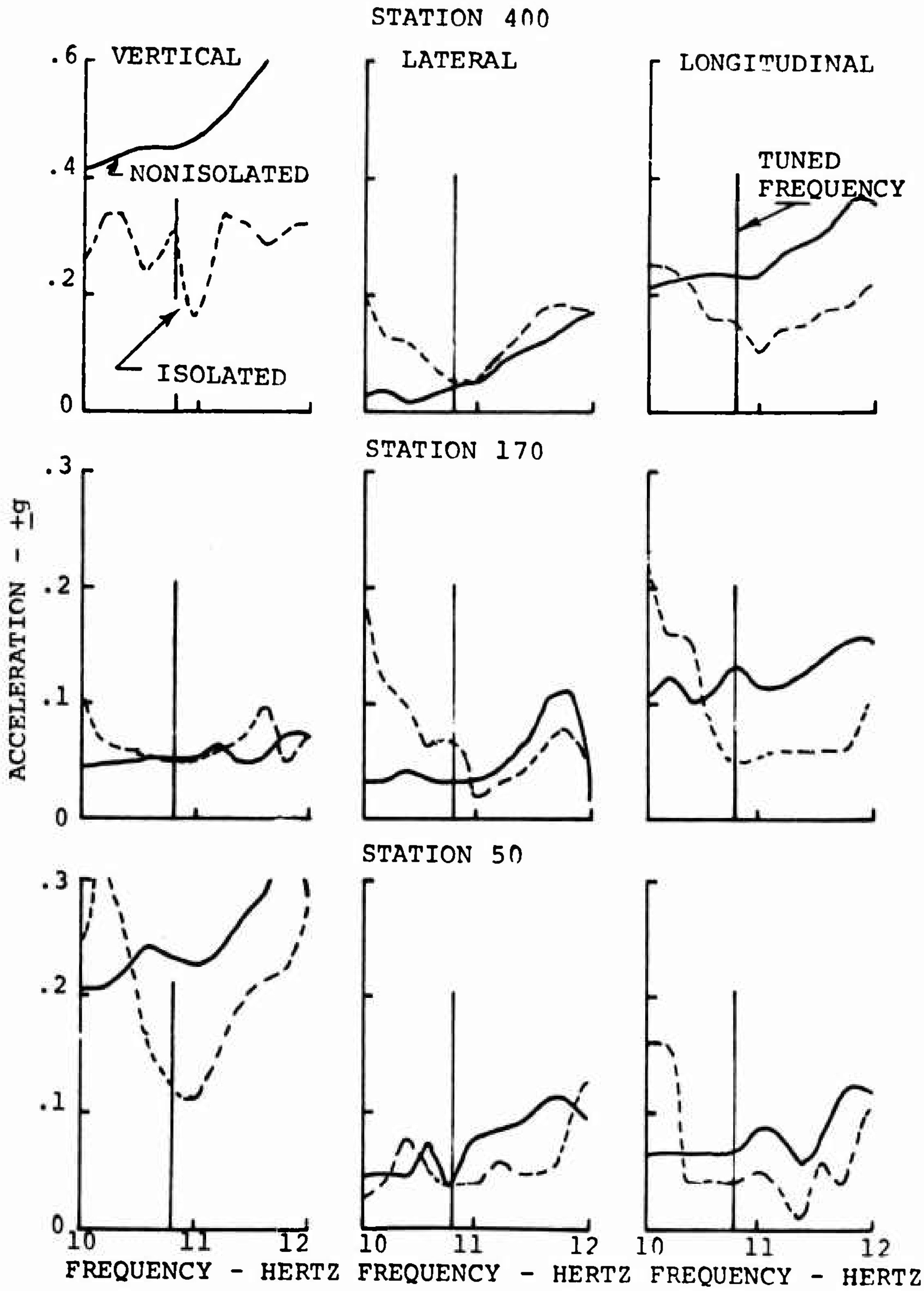


Figure 50. Responses of a Nonisolated and Three-DAVI-Isolated Two-Bladed Helicopter for Longitudinal Excitation.

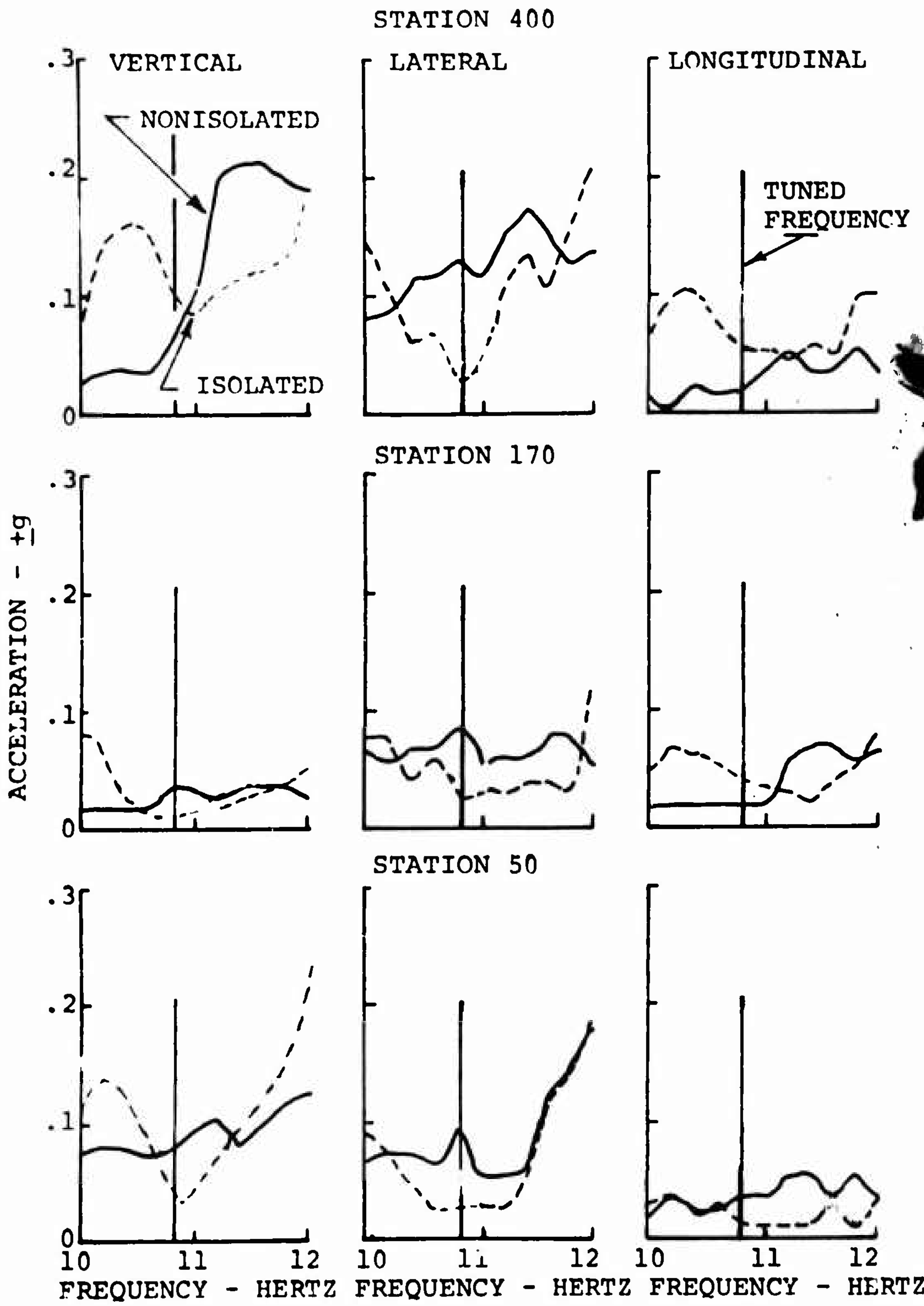


Figure 51. Responses of a Nonisolated and Three-DAVI-Isolated Two-Bladed Helicopter for Lateral Excitation.

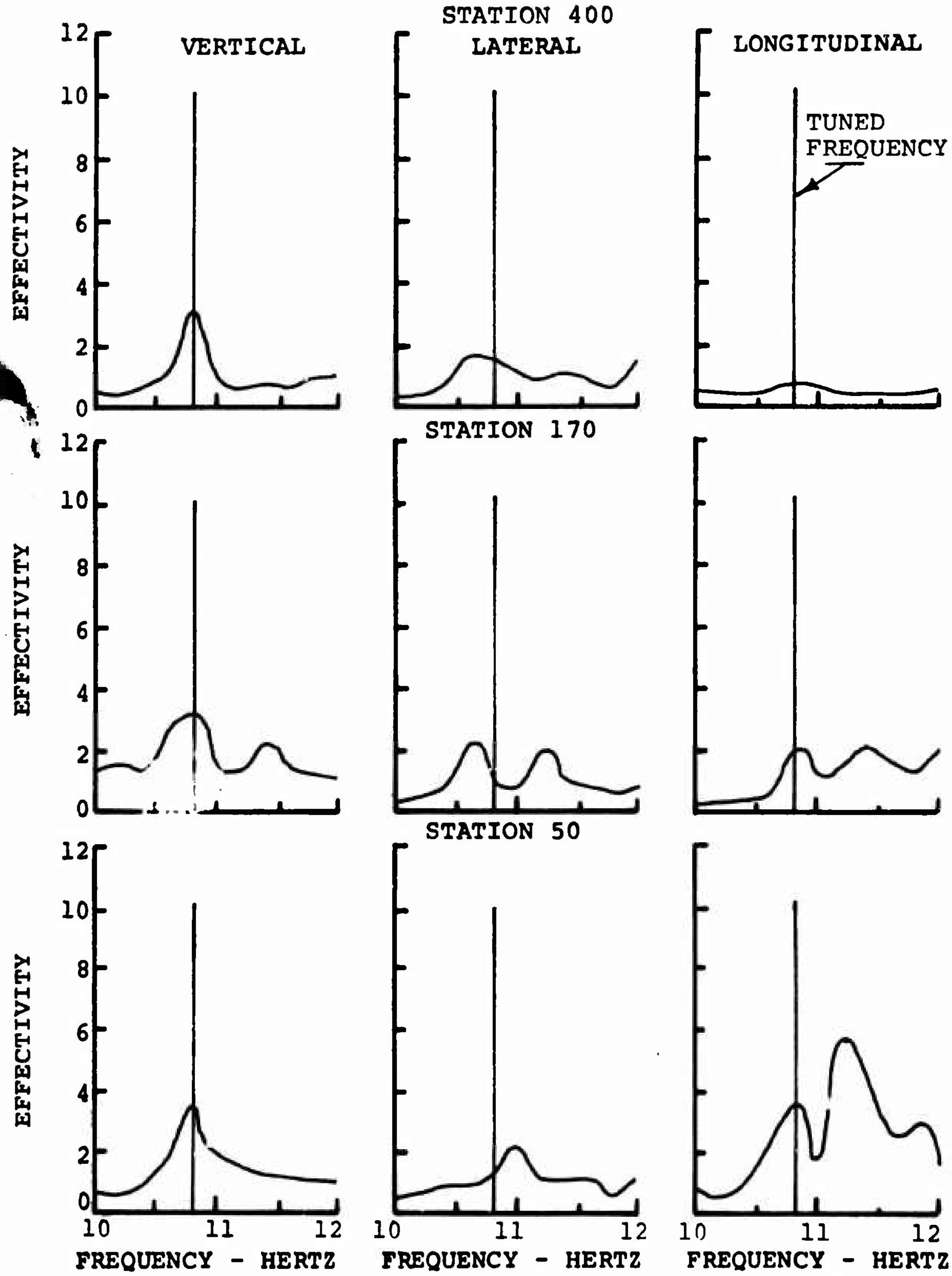


Figure 52. Effectivity of a Three-DAVI-Isolated Two-Bladed Helicopter for Vertical Excitation.

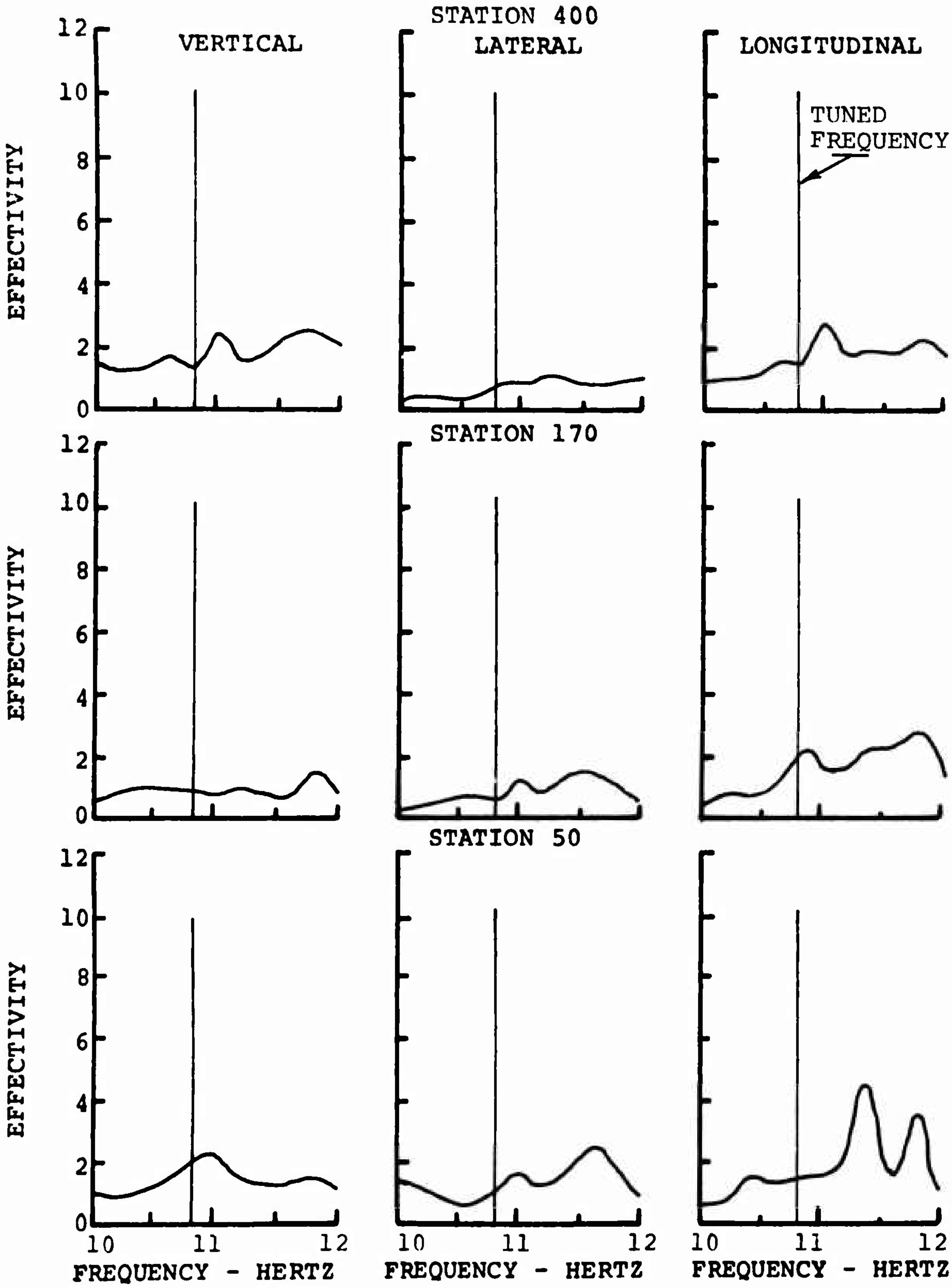


Figure 53. Effectivity of a Three-DAVI-Isolated Two-Bladed Helicopter for Longitudinal Excitation.

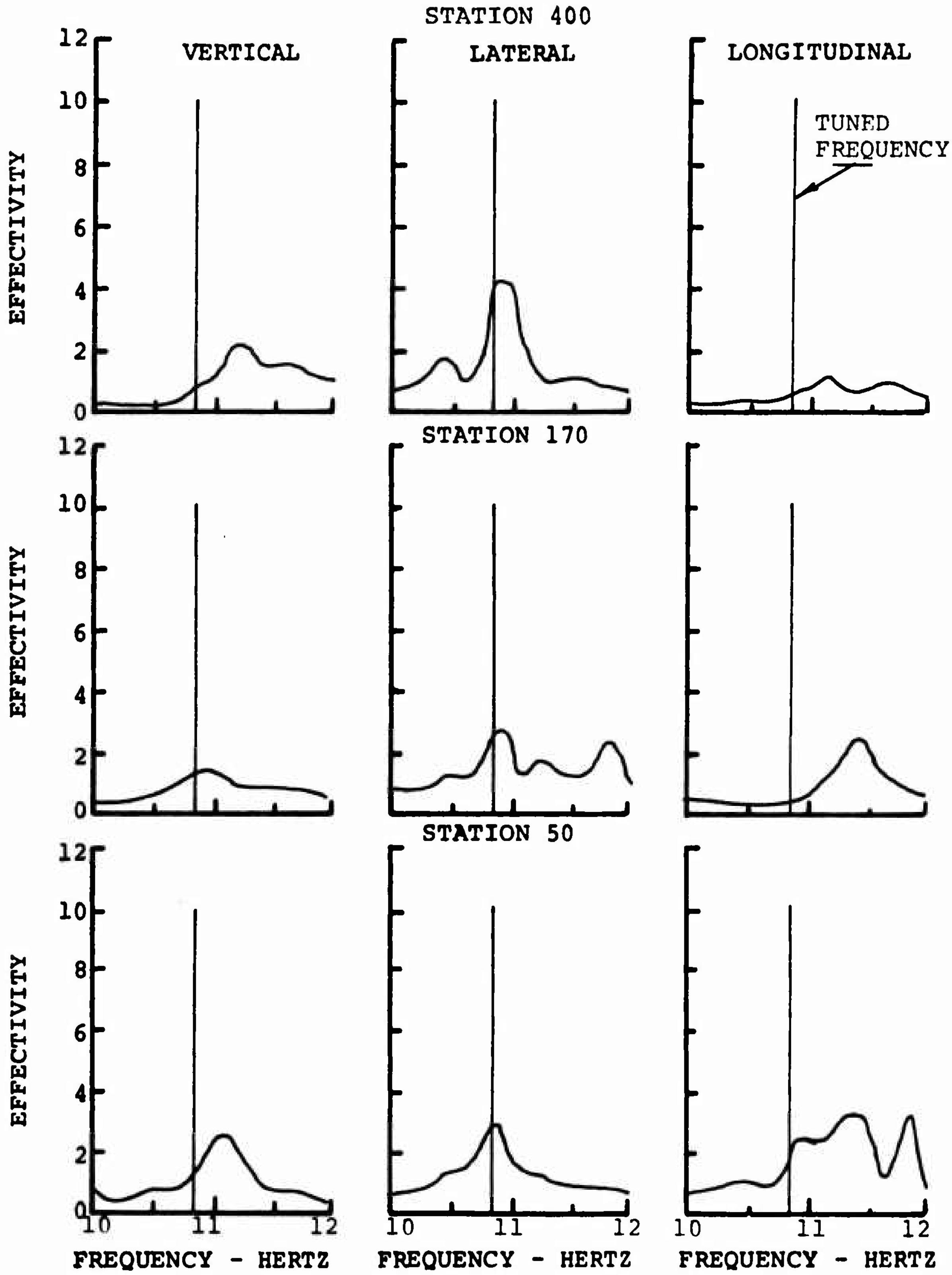


Figure 54. Effectivity of a Three-DAVI-Isolated Two-Bladed Helicopter for Lateral Excitation.

TABLE XXVI. PARAMETERS OF A THREE-DAVI CONFIGURATION ISOLATION SYSTEM FOR A TWO-BLADED HELICOPTER

Direction	Spring Rate (lb/in.)	Static Deflection (in.)	r (in.)	R (in.)	DAVI Inertia Bar Weight (lb)
Vertical	15,780	.11	2	7.5	27.06
In-Plane	17,483	-	2	9.14	20.75

Table XXVII shows the results obtained for the one-per-rev, two-per-rev, and four-per-rev frequencies, which are the predominant excitation frequencies of the two-bladed helicopter. These results are reported for shaking the helicopter with an excitation force of ±50 pounds at the one-per-rev frequency and with an excitation force of ±200 pounds at the four-per-rev frequency.

It is seen from Table XXVII that for the DAVI-isolated helicopter, there was an increase in the one-per-rev vibration level. Although the resulting vibration levels are low, the increase in vibration level is due to a near-resonant condition at one-per-rev and would make this configuration unacceptable from a finalized design standpoint.

It is also seen from Table XXVII that good results were obtained for the two-per-rev excitation. Some amplification did occur, however, in the direction of very low response of the nonisolated helicopter.

Table XXVIII shows the relative deflection obtained between the rotor and the fuselage for the three directions of excitation. These results are reported for shaking the helicopter with an excitation force of ±150 pounds at the one-per-rev frequency and with an excitation force of ±200 pounds at the four-per-rev frequency.

This table shows the relative deflection to be small. Due to the near-resonant condition at one-per-rev, the relative deflections for the one-per-rev excitation were greater than the other configurations tested.

TABLE XXVII. PREDOMINANT VIBRATION LEVELS OF THE TWO-BLADED HELICOPTER WITH A THREE-DAVI ISOLATION SYSTEM

Pickup Location		1-Per-Rev (±g)			2-Per-Rev (±g)			4-Per-Rev (±g)		
Sta	Direction	Non-Iso	Iso	T*	Non-Iso	Iso	T*	Non-Iso	Iso	T*
Vertical Excitation										
	Vert	.011	.056	5.09	.050	.031	.62	.494	.350	.71
400	Long.	.002	.014	7.00	.024	.030	1.25	.204	.120	.59
	Lat	.006	.022	3.67	.031	.030	.97	.073	.020	.27
	Vert	.009	.031	3.44	.093	.029	.31	.144	.075	.52
170	Long.	.001	.022	22.00	.050	.024	.48	.009	.092	10.22
	Lat	.002	.015	7.50	.023	.030	1.30	.148	.258	1.74
	Vert	.009	.017	1.89	.152	.043	.28	.307	.314	1.02
50	Long.	.001	.014	14.00	.055	.015	.27	.244	.080	.33
	Lat	.007	.007	1.00	.050	.032	.64	.076	.108	1.42
Longitudinal Excitation										
	Vert	.016	.060	3.75	.450	.307	.68	.431	.201	.47
400	Long.	.015	.031	2.07	.230	.139	.60	.246	.128	.52
	Lat	.007	.016	2.28	.044	.077	1.75	.070	.035	.50
	Vert	.003	.016	5.33	.051	.060	1.17	.013	.034	2.62
170	Long.	.010	.023	2.30	.133	.064	.48	.146	.100	.68
	Lat	.003	.008	2.67	.036	.076	2.11	.071	.098	1.37
	Vert	.014	.008	.57	.235	.132	.56	.358	.067	.19
50	Long.	.009	.018	2.00	.070	.046	.65	.228	.121	.53
	Lat	.004	.003	.75	.038	.047	1.23	-	.144	-
Lateral Excitation										
	Vert	.006	.048	8.00	.079	.097	1.23	.214	.421	1.97
400	Long.	.004	.025	6.25	.017	.064	3.76	.062	.221	3.56
	Lat	.008	.020	2.50	.131	.032	.24	.024	.045	1.87
	Vert	.002	.021	10.50	.034	.016	.46	.082	.088	1.07
170	Long.	.002	.014	7.00	.018	.050	2.78	.190	.224	1.18
	Lat	.004	.010	2.50	.086	.032	.37	.229	.321	1.40
	Vert	.005	.018	3.60	.083	.062	.74	.098	.412	4.20
50	Long.	.003	.016	5.33	.035	.016	.46	.188	.124	.66
	Lat	.003	.016	2.00	.102	.034	.33	.220	.170	.77

*T = Transmissibility; ratio isolated/nonisolated response.

TABLE XXVIII. RELATIVE DEFLECTION IN THE THREE-DAVI ISOLATION SYSTEM FOR A TWO-BLADED HELICOPTER

DAVI Location	Direction	Relative Deflection (±in.) 1-Per-Rev	2-Per-Rev	4-Per-Rev
Vertical Excitation				
Left Fwd	Vertical	.0142	.0187	.0007
	Longitudinal	.0019	.0017	.0005
	Lateral	.0023	.0033	.0005
Rt Fwd	Vertical	.0021	.0251	.0029
	Longitudinal	.0019	.0008	.0002
	Lateral	.0024	.0008	.0004
Rt Aft	Vertical	.0005	.0020	.0004
	Longitudinal	.0024	.0016	.0002
	Lateral	.0039	.0047	.0003
Longitudinal Excitation				
Left Fwd	Vertical	.0077	.0285	.0006
	Longitudinal	.0005	-	-
	Lateral	.0012	.0042	.0004
Rt Fwd	Vertical	.0019	.0108	.0007
	Longitudinal	.0018	.0043	.0003
	Lateral	.0015	.0094	.0006
Rt Aft	Vertical	.0003	.0036	.0001
	Longitudinal	.0016	.0054	.0006
	Lateral	.0023	.0244	.0005
Lateral Excitation				
Left Fwd	Vertical	.0103	.0199	.0010
	Longitudinal	-	-	-
	Lateral	.0016	.0127	.0007
Rt Fwd	Vertical	.0022	.0030	.0050
	Longitudinal	.0015	.0017	-
	Lateral	.0018	.0111	.0003
Rt Aft	Vertical	.0004	.0023	.0010
	Longitudinal	.0015	.0020	-
	Lateral	.0026	.0166	.0007

Although this system had a reduced spring rate as compared to the other systems tested, the deflections obtained indicate a minimum of relative deflection between the upper and lower bodies. These angular deflections should present no problems to coupling or shafting between the engine and transmission.

Hub Response

Figures 55 through 60 show the response of the hub versus frequency for all directions of excitation. It is seen from these figures that for the nonisolated helicopter for all directions of excitation, there was a structural resonance at approximately 15 Hertz. It is also seen for the nonisolated helicopter that there is a structural resonance between 22 and 23 Hertz; this is predominant in the vertical and lateral directions of excitation.

In comparing the DAVI-isolated three- and four-bladed helicopters to the nonisolated helicopter, it is seen that the predominant structural resonance was reduced to approximately 13 Hertz. However, below this frequency and at higher frequencies, the response of the hub for the DAVI-isolated helicopters was similar to the nonisolated helicopter.

For the DAVI-isolated two-bladed helicopter, it is seen that for the vertical direction of excitation, a natural frequency occurred at 10 Hertz for the four-DAVI configuration and at 6 Hertz for the three-DAVI configuration. For the longitudinal direction of excitation, it is seen that the four-DAVI configuration had natural frequencies at 8, 10, and 15 Hertz and the three-DAVI configuration had natural frequencies at 6 and 10 Hertz. For the lateral direction of excitation, the four-DAVI configuration had a natural frequency at 10 Hertz and the three-DAVI configuration had natural frequencies at 6 and 10 Hertz. All of these frequencies are above one-per-rev excitation frequency, which was the design goal of the isolation system.

From these figures, the response of the hub at the predominant excitation frequencies of the three-rotor configurations tested can be obtained. Table XXIX shows these responses. These results are reported for shaking the helicopter at the one-per-rev excitation frequency with a force level of 0.1 of the n-per-rev force level and at the 2n-per-rev excitation with a force level of 0.4 of the n-per-rev force level. For the three- and four-bladed rotor, this n-per-rev force level was ±250 pounds; for the two-bladed rotor, the n-per-rev force level was ±500 pounds.

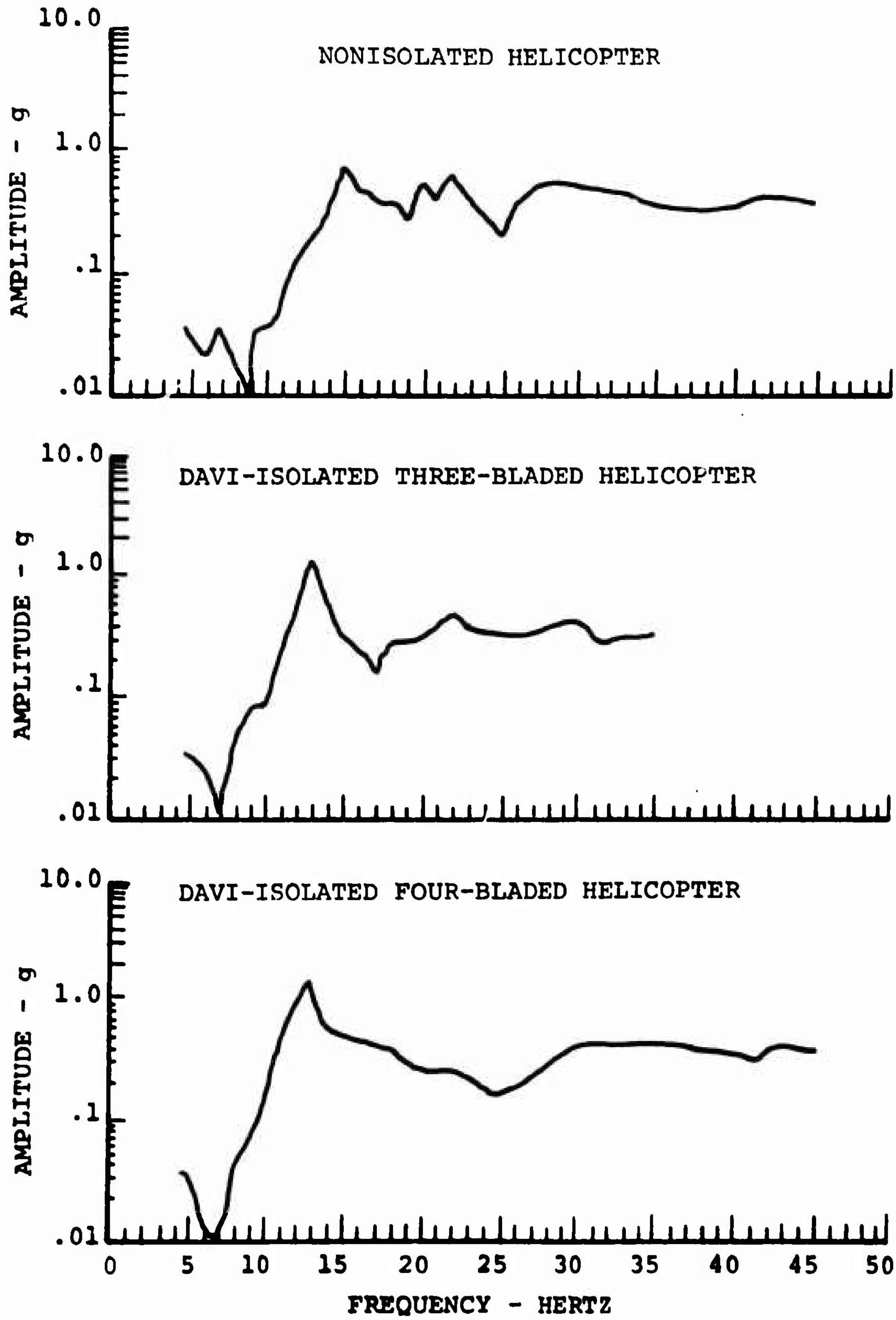


Figure 55. Vertical Response of the Hub for the Vertical Direction of Excitation.

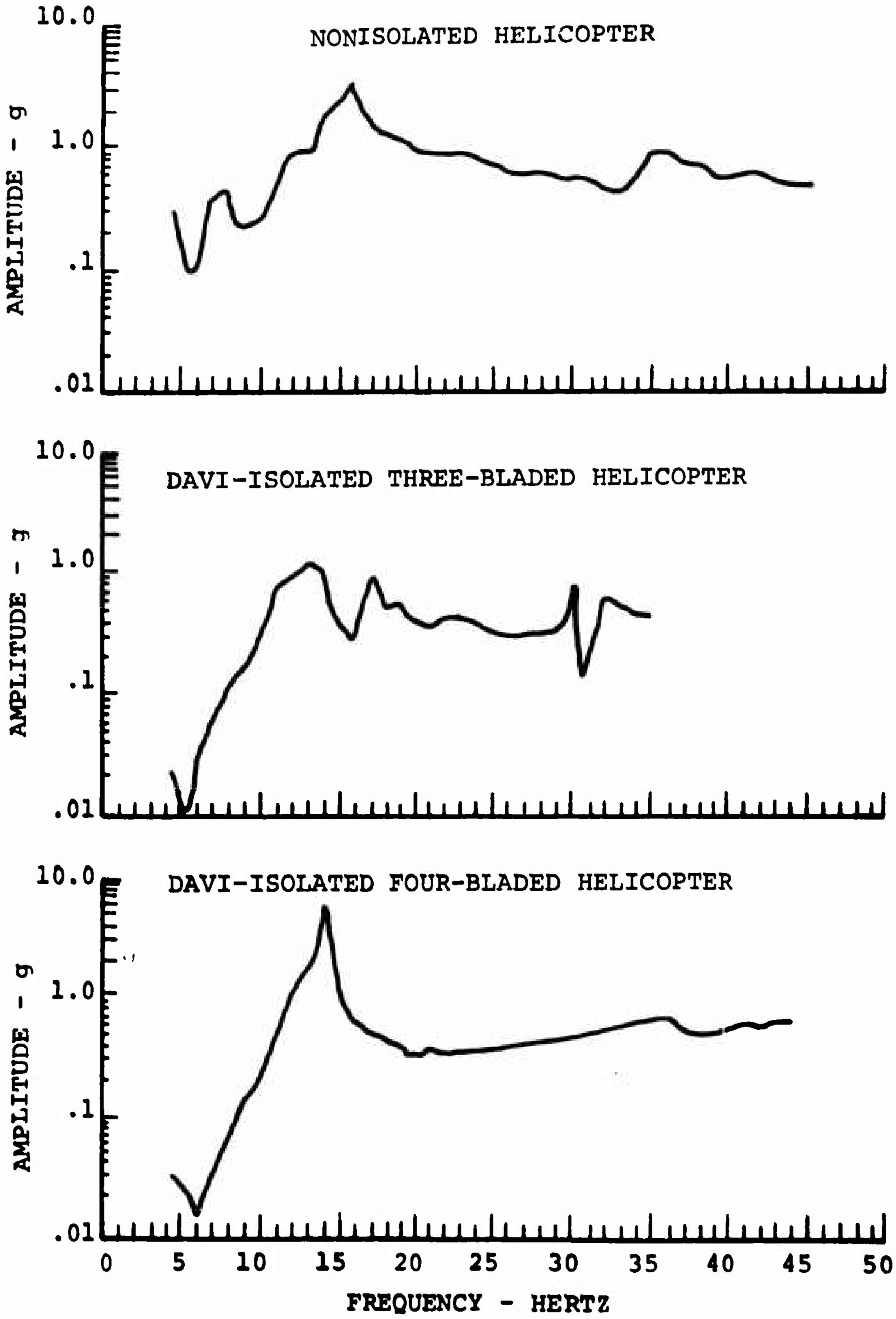


Figure 56. Longitudinal Response of the Hub for the Longitudinal Direction of Excitation.

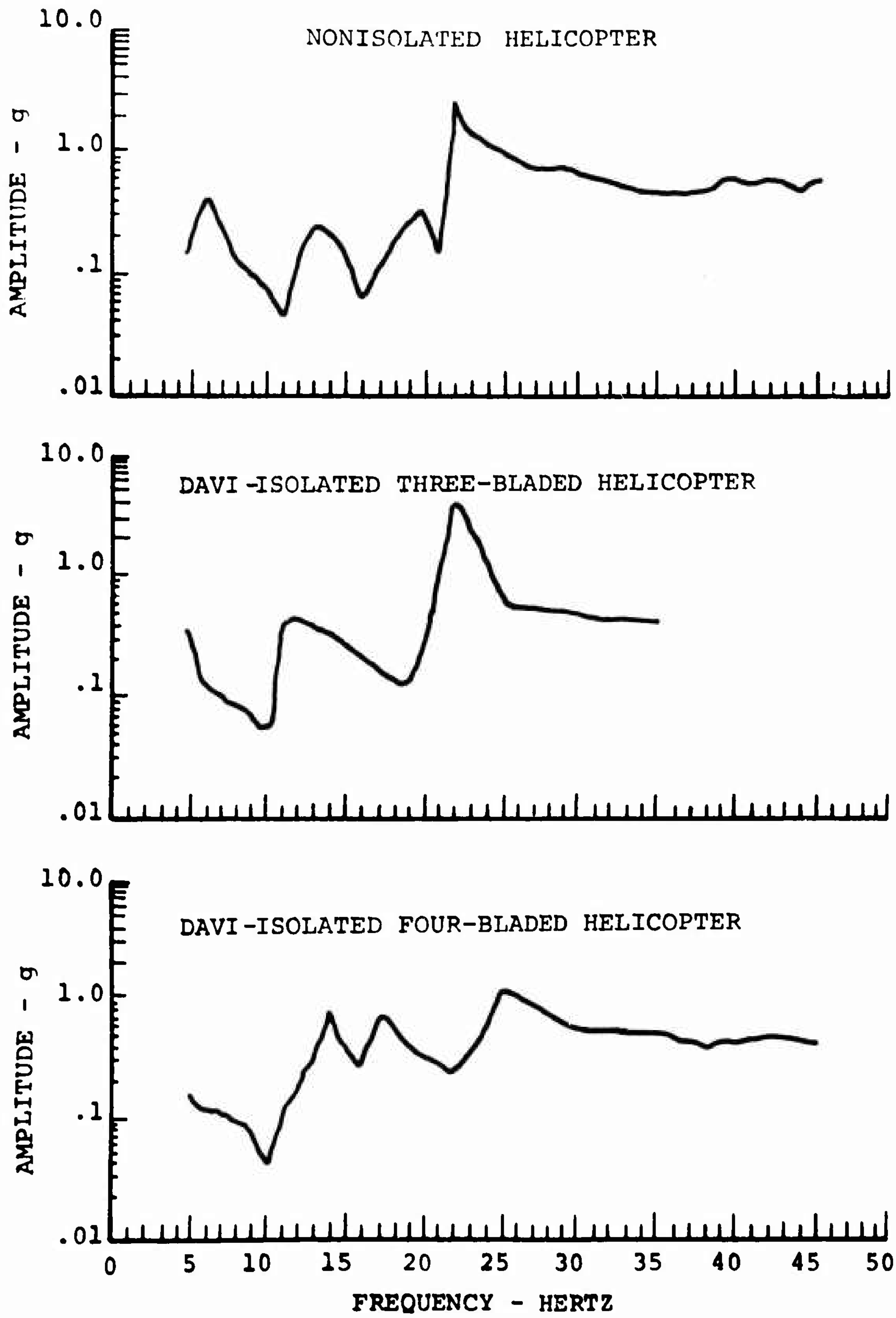


Figure 57. Lateral Response of the Hub for the Lateral Direction of Excitation.

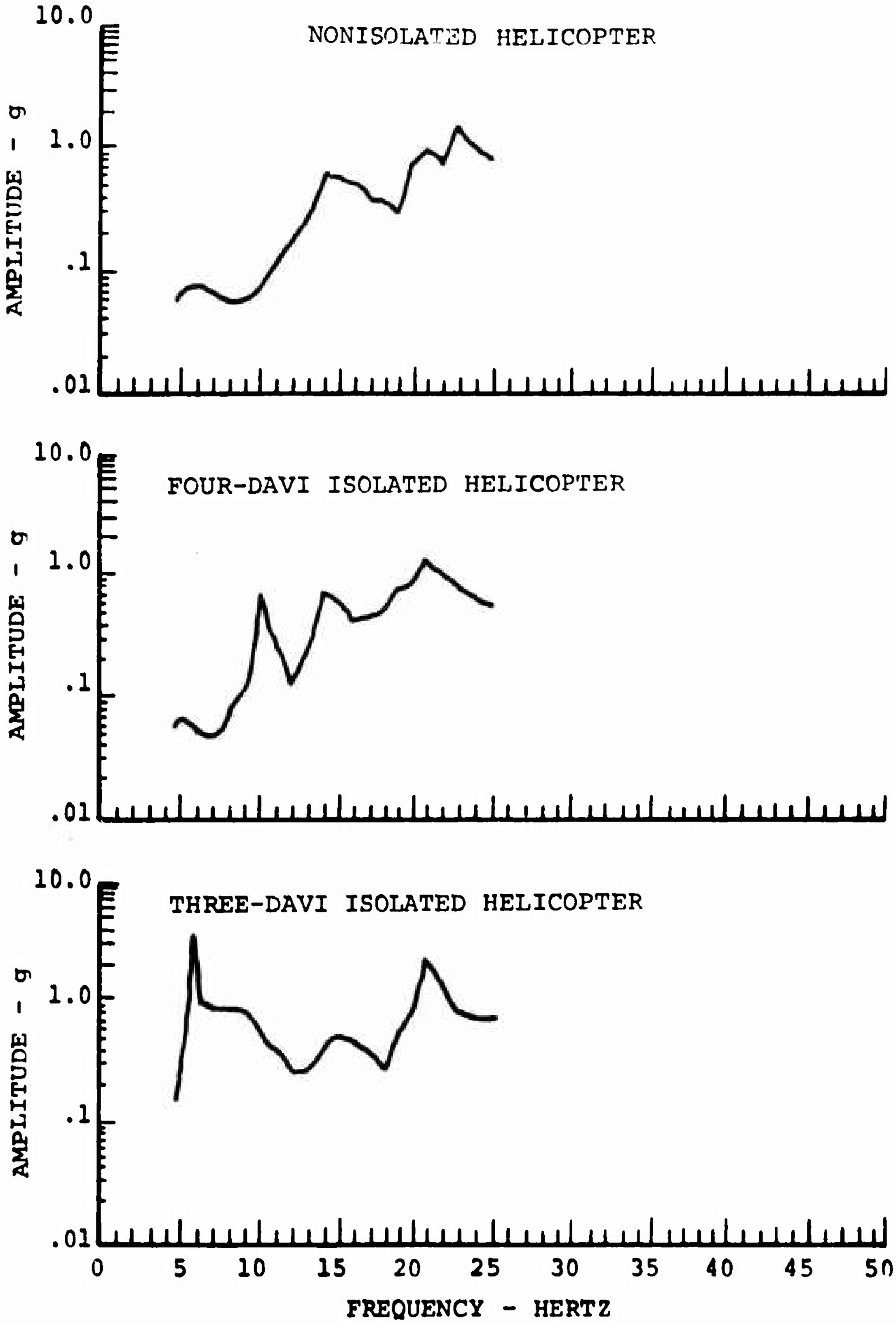


Figure 58. Vertical Response of the Hub of a Two-Bladed Helicopter for the Vertical Direction of Excitation.

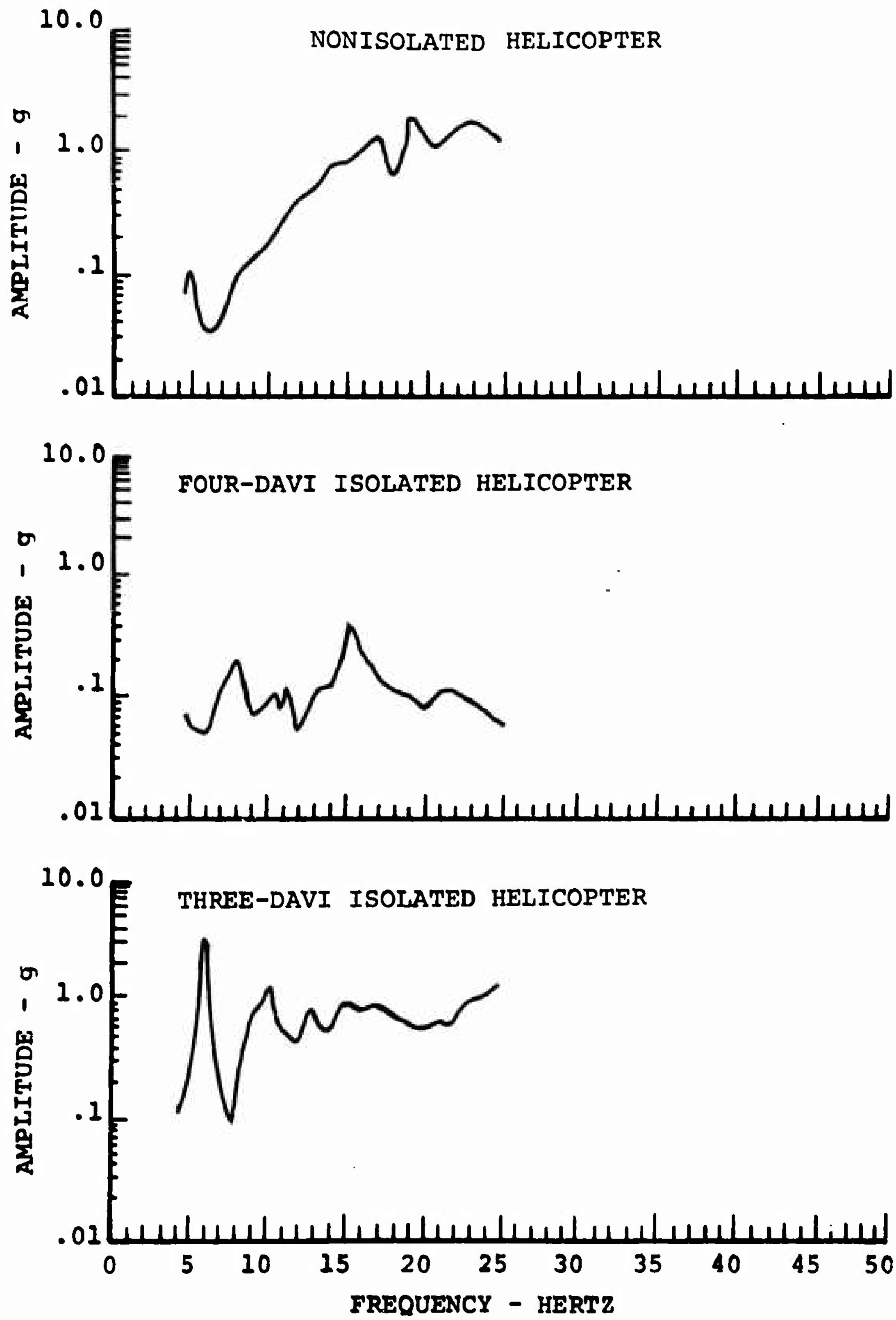


Figure 59. Longitudinal Response of the Hub of a Two-Bladed Helicopter for the Longitudinal Direction of Excitation.

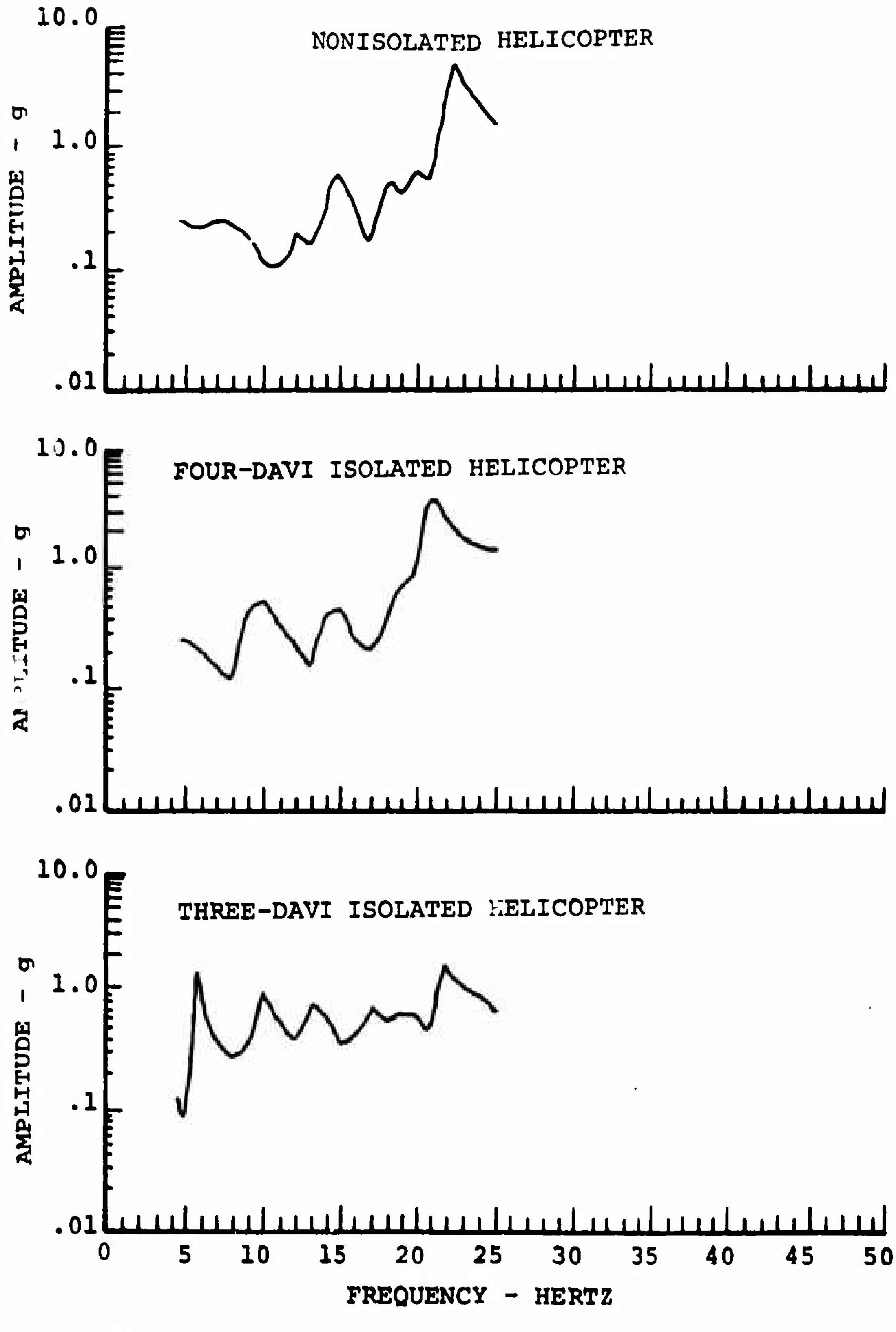


Figure 60. Lateral Response of the Hub of a Two-Bladed Helicopter for the Lateral Direction of Excitation.

It is seen from this table that for the DAVI-isolated three- and four-bladed rotors, the one-per-rev accelerations in all directions were essentially the same. The table also shows that for the three- and four-bladed rotors for the vertical and longitudinal directions of excitation, there was a substantial decrease in hub acceleration for the DAVI-isolated vehicles at the n-per-rev excitation. For the 2n-per-rev excitation, the accelerations at the hub of the DAVI-isolated vehicles and the nonisolated vehicle were of the same general magnitude.

For the two-bladed helicopter, it is seen that for the one-per-rev excitation, the four-DAVI configuration had essentially the same response as the nonisolated helicopter, and the three-DAVI configuration had a greater response than the nonisolated helicopter. This greater response was due to a near-resonant condition at one-per-rev.

TABLE XXIX. HUB RESPONSE

Direction of Excitation	No. of Blades	No. of DAVI's	Frequency of Excitation: 1-Per-Rev (±g)		n-Per-Rev (±g)		2n-Per-Rev (±g)	
			Iso	Non-Iso	Iso	Non-Iso	Iso	Non-Iso
Vertical	2	3	.095	.008	.408	.096	.495	.244
	2	4	.005	.008	.337	.096	.395	.244
	3	4	.003	.003	.326	.613	.157	.205
	4	4	.003	.003	.241	.542	.117	.116
Longitudinal	2	3	.068	.008	.750	.275	.244	.696
	2	4	.007	.008	.412	.275	.467	.696
	3	4	.003	.005	.552	1.897	.288	.172
	4	4	.003	.005	.341	.707	.199	.204
Lateral	2	3	.067	.028	.626	.110	.539	.521
	2	4	.024	.028	.389	.110	.864	.521
	3	4	.013	.016	.265	.169	.209	.261
	4	4	.017	.016	.300	.319	.180	.215

The DAVI-isolated configurations for the two-bladed rotor systems had a greater response at two-per-rev excitation frequency than the nonisolated helicopter. Also, for the two-bladed rotor systems, the DAVI-isolated configurations had a greater response at the four-per-rev excitation frequency than the nonisolated helicopter in the vertical and lateral directions of excitation.

Mechanical Instability

Mechanical instability is caused by the coupling between the in-plane hub motion and in-plane blade motions. The center mechanical instability, which is the point at which the instability is most critical, is given by the following relationship:

$$\omega_n + \omega_B = \Omega_{M,I} \tag{2}$$

in which

ω_n = in-plane natural frequencies;

ω_B = in-plane blade natural frequency;

$\Omega_{M,I}$ = rotor speed for center of mechanical instability.

It is seen from the above equation that, depending upon the natural frequencies of the in-plane isolation system, mechanical instability could occur in flight.

For semirigid rotor systems, in which the in-plane natural frequencies of the blade are usually above one-per-rev of the rotor, mechanical instability is not a problem. However, for articulated rotor systems, in which the natural frequency of the rigid body mode of the blade due to lag hinge offset is well below one-per-rev, mechanical instability could occur in flight. The in-plane natural frequency of an articulated rotor blade is approximately $.2\Omega$. Therefore, by knowing the hub natural frequencies and the blade natural frequency, the center of mechanical instability can be determined. Table XXX gives the results of these calculations. The in-plane natural frequencies are obtained from Figures 56, 57, 59, and 60. Only the lowest in-plane natural frequency is shown, since this is the most critical.

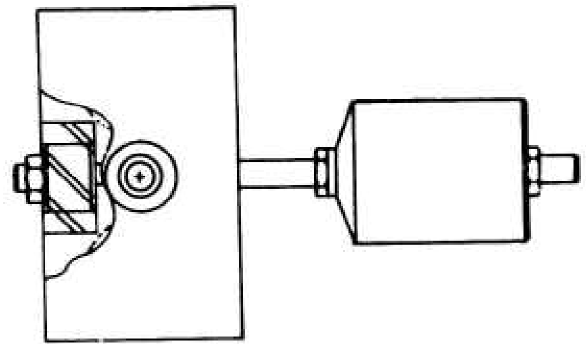
It is seen from Table XXX that the DAVI system was designed to have a natural frequency above the operating range of the helicopter; therefore, the possibility of mechanical instability occurring in flight is eliminated.

TABLE XXX. CENTERS OF MECHANICAL INSTABILITY				
Configuration	Rotational Frequency (Hertz) (Ω)	In-Plane Hub Natural Frequency (Hertz) (ω_n)	(ω_n/Ω)	Center of Mechanical Instability ($\Omega_{M,I}/\Omega$)
Four-Bladed	4.95	14.0	2.83	3.03
Three-Bladed	4.97	11.5	2.31	2.51
Two-Bladed 4-DAVI	5.40	8.0	1.48	1.68
Two-Bladed 3-DAVI	5.40	6.0	1.11	1.31

WEIGHTS

The objective of this program was to demonstrate the feasibility of rotor isolation using the DAVI concept. For this test program, a three-dimensional DAVI isolation system incorporating four DAVI's of a single size suitable for installation in either a 6500-pound or a 10,000-pound helicopter was designed. Isolator parameters were not optimized for either gross weight or any one rotor configuration. Consequently, optimization for performance or minimum weight was not attempted.

Figure 61 shows a breakdown of the actual weights of the three-dimensional DAVI used in this program. The weight of the movable weight (G) is not shown in this breakdown since the weight depends upon the configuration tested. It is seen from this figure that the DAVI was heavy. Neglecting the weight of the movable weights on the inertia bar rods, the three-dimensional DAVI isolation system weighed 1.36 percent of the gross weight of a 10,000-pound helicopter. For the four-bladed configuration tested, the weight of the movable weights on the inertia bar rods of each DAVI was a total of 17.5. Thus, the total system weighed 2.06 percent of the gross weight of a 10,000-pound helicopter. Further reduction in weight in this design could be accomplished by lightening holes in the housing and isolated plate. Therefore, for a 10,000-pound helicopter, a DAVI isolation system can be designed for less than 2 percent of the gross weight.



PART	WEIGHT (LB)
A	10.875
B	12.500 (4-spring total)
C	3.875
D	3.250
E	2.563
F	1.063
G	-

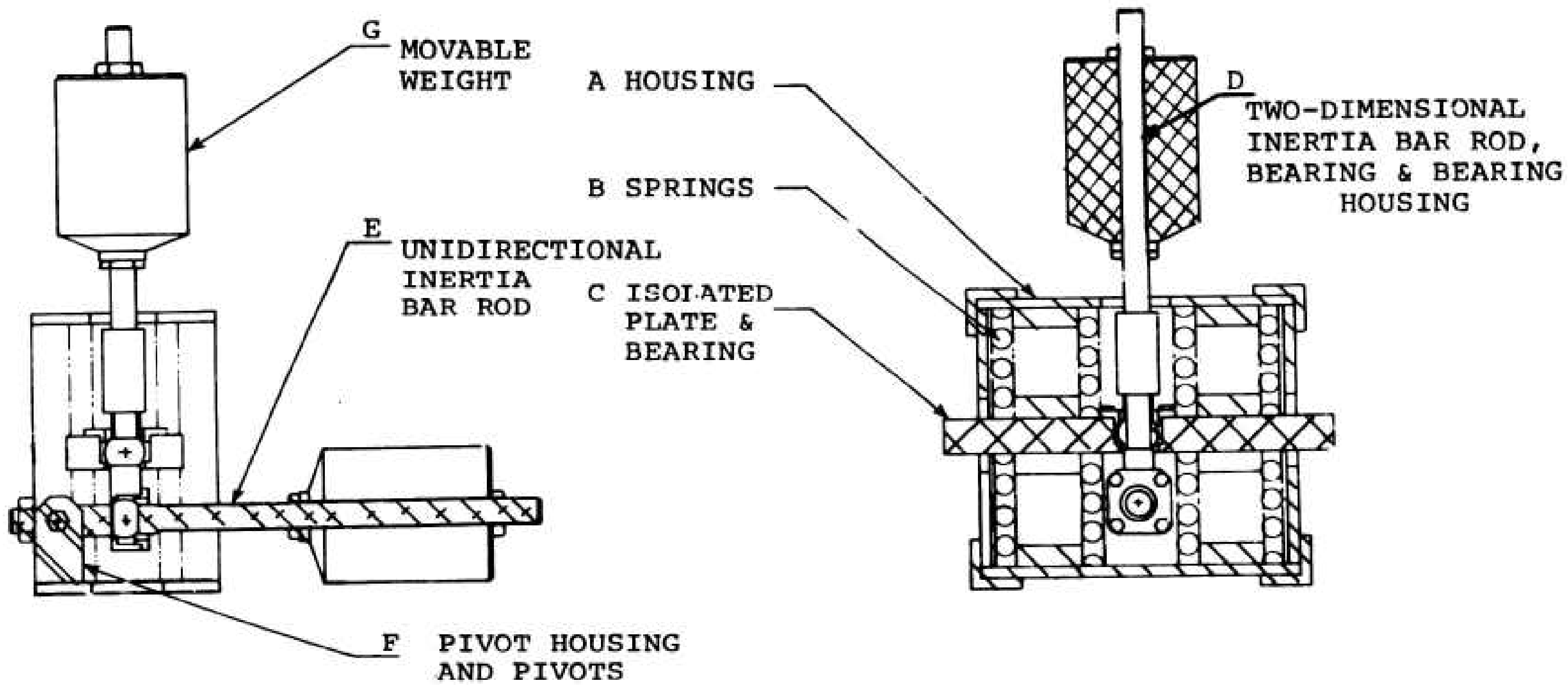


Figure 61. Weights Breakdown of Three-Dimensional DAVI.

Figure 62 shows a possible schematic of a three-dimensional DAVI for a 6500-pound helicopter. It is seen from this schematic that this DAVI is much more compact than the DAVI used in this test. This design requires only two springs. Also, by designing the springs to have a lower spring rate in the in-plane direction than in the vertical direction, the weight of the two-dimensional inertia bar is less than the vertical bar. Comparing this schematic to the actual weight of the DAVI used in this program, Table XXXI gives an estimated weight of a DAVI for a 6500-pound helicopter.

The estimate of the inertia bar weight is based upon a static deflection of .125 inch and the fact that the in-plane spring rate is 75 percent of the vertical spring rate. For a 6500-pound helicopter, this four-DAVI isolation system would weigh 116.4 pounds, or 1.79 percent of the gross weight.

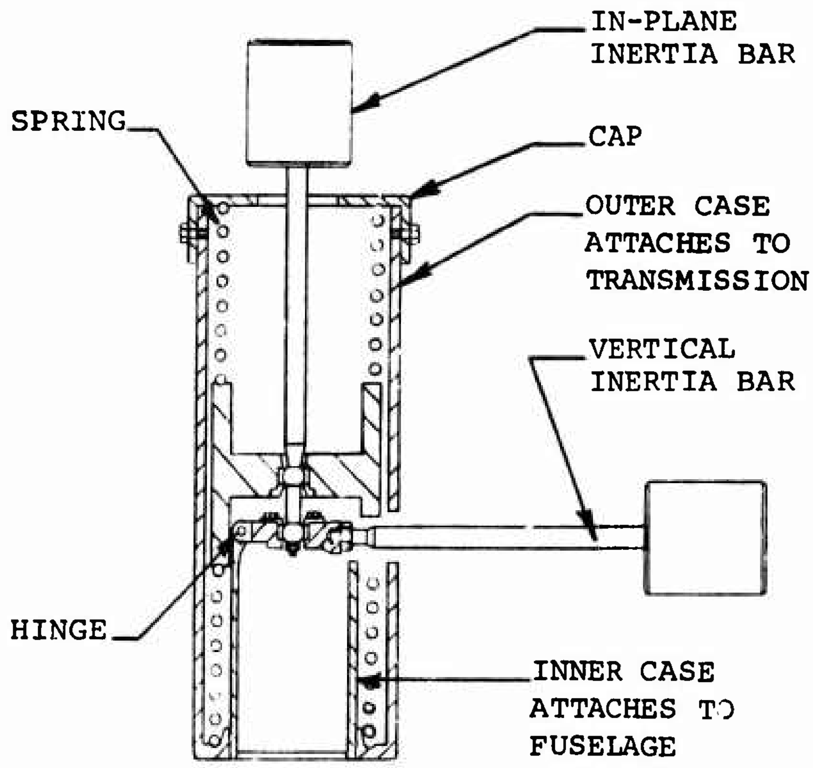


Figure 62. Schematic of Three-Dimensional DAVI for a 6500-Pound Helicopter.

TABLE XXXI. ESTIMATED WEIGHT OF A THREE-DIMENSIONAL DAVI FOR A 6500-POUND HELICOPTER

Part	Weight (lb)
Inner and Outer Cases	3.5
Springs	6.0
Vertical Inertia Bar Rod, Movable Weight and Bearings	11.2
In-Plane Inertia Bar Rod, Movable Weight and Bearings	8.4
TOTAL	29.1

The weight of the DAVI isolation system could be considered a weight penalty. However, in the development of most helicopters, structural stiffening and vibration devices, such as vibration absorbers, are used to minimize the vibration problems, thus increasing the design weights. Utilizing the DAVI for rotor isolation will minimize this type of design change and possibly will result in a weight saving rather than a penalty.

Reliability

A reliability analysis of the DAVI isolation system was not done in this program. However, in Reference 6, a reliability analysis was done. This analysis showed that the reliability of the DAVI isolation compares favorably to the reliability of other critical components in helicopter systems.

For the DAVI's used in this program, failures of the input or output pivots would not lead to a catastrophic loss of a vehicle but, at worst, a mandatory abort as indicated in the referenced analysis. A failure of the springs in this DAVI would not lead to complete separation of the attachment, since stops are provided in the housing permitting ±0.5 inch maximum displacement of the isolated plate.

ANALYSIS

An analysis was conducted for the DAVI-isolated four-bladed configuration to determine the possible source of the discrepancy in antiresonant frequency obtained for the vertical and longitudinal directions of excitation. This analysis was conducted on the twelve-degrees-of-freedom digital program developed under USAAVLABS Contract DA 44-177-AMC-420(T) and reported in Reference 6. This study was made assuming that the DAVI was working properly in the vertical direction, and the problem was associated with the in-plane direction of the DAVI. Table XXXII shows the in-plane configurations studied.

TABLE XXXII. DAVI-ISOLATED FOUR-BLADED CONFIGURATION

Configuration No.	Description
1	Normal DAVI and Spring System
2	No DAVI and Zero Spring
3	No DAVI and Normal Spring
4	No DAVI and Very Stiff Spring

Table XXXIII gives the results of this study. These results are given as effectivity for the five rigid body modes studied. It is seen from this table that for configurations 3 and 4, a lower antiresonant frequency was predicted for the longitudinal and lateral directions of excitation than for the vertical directions of excitation. Configuration 3 could possibly simulate slop in the bearings of the in-plane inertia bar which would allow normal spring action but make the inertia bar ineffective. Configuration 4 could represent binding in the bearings of the in-plane inertia bar and thus stiffen the spring system. An actual change in the bearings of the DAVI system did alleviate the problem; namely, the same antiresonant frequency was obtained in the longitidunal and vertical directions of excitation, as shown by subsequent tests.

An analysis was also made of the DAVI-isolated two-bladed helicopter to determine the effects of four-DAVI and three-DAVI isolation systems. Table XXXIV gives the configurations studied.

Table XXXV gives the results of this study. The lower spring rate systems did give a slightly larger bandwidth of isolation for the vertical direction of excitation due to the fact that the natural frequency of the softer system was slightly reduced.

TABLE XXXIII. EFFECTIVITY OF THE DAVI-ISOLATED FOUR-BLADED ROTOR

Freq (Hertz)	Effectivity																			
	E_z				E_x				E_α				E_y				E_θ			
	Config No.				Config No.				Config No.				Config No.				Config No.			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
19.0	8	8	8	8	62	116	233	303	22	24	25	25	11	12	9	9	9	9	8	8
19.2	11	11	11	11	67	171	44	50	29	35	44	43	15	18	14	14	13	14	12	12
19.4	17	17	17	17	89	281	25	28	45	58	173	145	22	29	28	20	22	22	22	22
19.6	35	35	35	35	167	613	18	20	92	126	97	118	46	63	541	359	41	49	81	78
19.8	2×10^4	2×10^4	2×10^4	2×10^4	1×10^5	4×10^5	14	16	7×10^4	8×10^4	39	44	4×10^4	4×10^4	35	38	4×10^4	3×10^4	56	61
20.0	38	38	38	38	153	711	11	13	95	145	25	27	48	73	18	19	44	56	22	23
20.2	20	20	20	20	75	381	10	11	49	78	18	20	25	39	12	13	23	30	14	15
20.4	14	14	14	14	50	270	9	10	33	55	15	16	17	28	9	10	15	21	10	11
20.6	11	11	11	11	37	215	8	9	26	44	12	14	13	22	8	8	12	17	9	9
20.8	9	9	9	9	30	182	7	8	21	37	11	12	11	19	7	7	10	14	7	8
21.0	8	8	8	8	25	160	6	8	18	33	9	11	9	17	6	6	9	13	6	7

TABLE XXXIV. DAVI-ISOLATED TWO-BLADED CONFIGURATION	
Configuration No.	Description
1	Four-DAVI System
2	Three-DAVI Nonsymmetrical System
3	Three-DAVI Symmetrical System
4	Four-DAVI System With Same Overall Spring Rate as Three-DAVI System

An analysis was made of a simple DAVI isolated platform to determine the effect of offset of springs from the pivot axis of the inertia bar and the effect of the distance between the pivots of the inertia bar. For the schematic in Figure 63, the equations of motion can be derived.

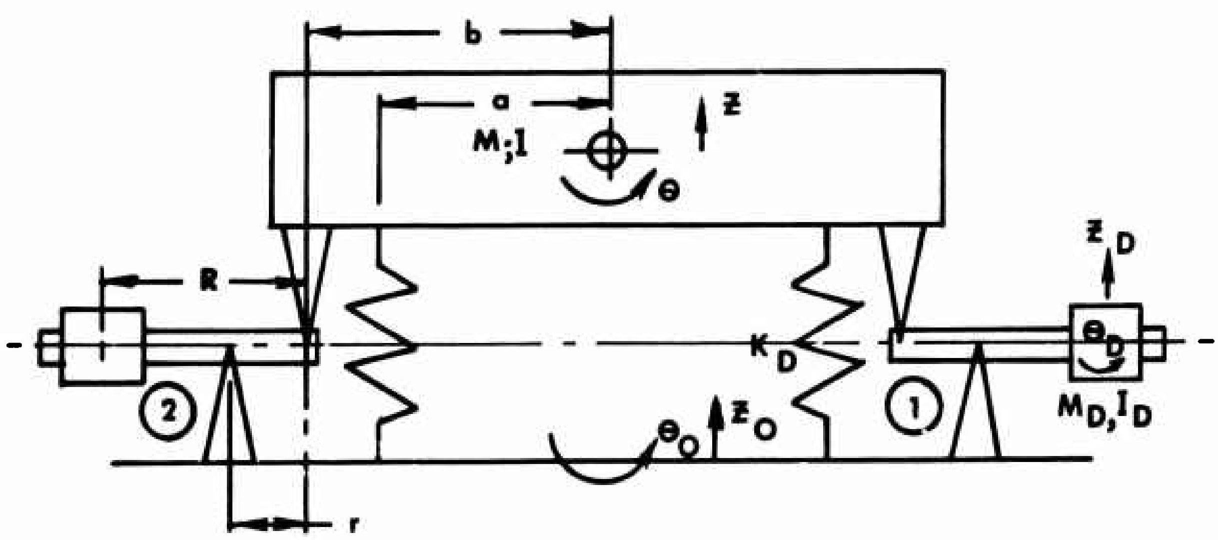


Figure 63. Schematic of a DAVI-Isolated Platform.

TABLE XXXV. EFFECTIVITY OF THE DAVI-ISOLATED TWO-BLADED ROTOR

	Effectivity																			
	E_z				E_x				E_α				E_y				E_θ			
	Config No.				Config No.				Config No.				Config No.				Config No.			
Freq (Hertz)	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
10.0	.3	.1	.1	.1	2	2	.9	3	2	2	1	3	.9	.1	2	1	.9	.1	2	1
10.2	.1	.5	.5	.5	3	2	3	4	3	3	3	5	2	1	3	2	2	1	3	2
10.4	.4	1	1	1	5	4	5	6	5	5	7	8	3	3	5	4	3	3	6	4
10.6	2	4	4	4	10	10	12	13	12	11	16	17	6	6	10	8	7	7	12	9
10.8	4×10^2	5×10^2	5×10^2	6×10^2	1×10^3	1×10^2	1×10^3	2×10^3	2×10^3	4×10^2	2×10^3	2×10^3	8×10^2	7×10^2	1×10^3	1×10^3	1×10^3	8×10^2	1×10^3	1×10^3
11.0	4	7	6	6	10	10	11	12	15	17	19	20	7	7	9	8	9	9	13	11
11.2	3	4	4	4	4	3	4	4	8	8	10	10	3	3	3	3	5	4	5	5
11.4	2	2	2	3	.4	.5	.4	.2	5	8	27	4	.5	1	1	.2	.2	12	3	.6
11.6	2	3	2	2	17	12	11	37	5	7	7	5	85	38	8	12	5	5	14	6
11.8	2	2	2	2	11	26	33	11	4	5	5	5	6	7	49	11	3	4	7	4
12.0	2	2	2	2	6	10	11	8	4	5	5	4	4	5	11	6	3	3	5	4

From the above schematic, the energies of the system are

$$T = \frac{1}{2}M\dot{z}^2 + \frac{1}{2}I\dot{\theta}^2 + \frac{1}{2}M_{D_1}\dot{z}_{D_1}{}^2 + M_{D_2}\dot{z}_{D_2}$$

$$+ \frac{1}{2}I_{D_1}\dot{\theta}_{D_1}{}^2 + \frac{1}{2}I_{D_2}\dot{\theta}_{D_2}{}^2 \qquad (3)$$

$$V = \frac{1}{2}K_{D_1}[(z + a\theta) - (z_o + a\theta_o)]^2 + \frac{1}{2}K_{D_2}[(z - a\theta) - (z_o - a\theta_o)]^2$$

(4)

But for DAVI 1,

$$\theta_{D_1} = \frac{z_o - z}{r} + \frac{b}{r}(\theta_o - \theta) + \theta_o \qquad (5)$$

$$z_{D_1} = (1 - \frac{R}{r})z + \frac{R}{r}z_o + b(1 - \frac{R}{r})\theta + \frac{R}{r}(b + r)\theta_o \qquad (6)$$

and for DAVI 2,

$$\theta_{D_z} = -\frac{z_o - z}{r} + \frac{b}{r}(\theta_o - \theta) + \theta_o \qquad (7)$$

$$z_{D_2} = (1 - \frac{R}{r})z + \frac{R}{r}z_o - b(1 - \frac{R}{r})\theta - \frac{R}{r}(b + r)\theta_o \qquad (8)$$

Substituting Equations (5), (6), (7) and (8) into Equation (3), the kinetic energy equation becomes

$$T = \frac{1}{2}M\dot{z}^2 + \frac{1}{2}I\dot{\theta}^2 + \frac{1}{2}M_{D_1}[(1 - \frac{R}{r})\dot{z} + \frac{R}{r}\dot{z}_o + b(1 - \frac{R}{r})\dot{\theta} + \frac{R}{r}(b + r)\dot{\theta}_o]^2$$
$$+ \frac{1}{2}I_{D_1}[\frac{\dot{z}_o - \dot{z}}{r} + \frac{b}{r}(\dot{\theta}_o - \dot{\theta}) + \dot{\theta}_o]^2 + \frac{1}{2}M_{D_2}[(1 - \frac{R}{r})\dot{z} + \frac{R}{r}\dot{z}_o$$
$$- b(1 - \frac{R}{r})\dot{\theta} - \frac{R}{r}(b + r)\dot{\theta}_o]^2 + \frac{1}{2}I_{D_2}[\frac{\dot{z}_o - \dot{z}}{r} - \frac{b}{r}(\dot{\theta}_o - \dot{\theta}) - \dot{\theta}_o]^2$$

(9)

Applying Lagrange's equation to Equations (3) and (4), the equations of motion become, assuming symmetry in DAVI's 1 and 2,

$$(M + 2M_R)\ddot{z} + 2K_D z - 2M_A \ddot{z}_o - 2K_D z_o = 0 \tag{10}$$

$$(I + 2M_R b^2)\ddot{\theta} + 2K_D a^2 \theta - 2M_A b(b + r)\ddot{\theta}_o - 2K_D a^2 \theta_o = 0 \tag{11}$$

where

$$M_A = M_D(\frac{R}{r})(\frac{R}{r} - 1) + \frac{I_D}{r^2} \tag{12}$$

$$M_R = M_D(\frac{R}{r} - 1)^2 + \frac{I_D}{r^2} \tag{13}$$

Equations (11) and (12) are decoupled because of the assumed symmetry of the system. Assuming a steady-state solution of the form $e^{i\omega t}$, and solving for the translational and rotational transmissibilities, Equations (10) and (11) become

$$\frac{z}{z_\theta} = \frac{2K_D - 2M_A\omega^2}{2K_D - [M + 2M_R]\omega^2} \tag{14}$$

$$\frac{\theta}{\theta_o} = \frac{2K_D a^2 - 2M_A b(b + r)\omega^2}{2K_D a^2 - (I + 2M_R b^2)\omega^2} \tag{15}$$

It is seen from Equations (14) and (15) that zero transmissibility or the antiresonant frequency is obtained when the numerator is zero, or

$$\omega^2_{A_T} = \frac{K_D}{M_A} \tag{16}$$

$$\omega^2_{A_R} = \frac{K_D a^2}{M_a b(b + r)} \tag{17}$$

It is seen from Equations (16) and (17) that there is a discrepancy between the translational antiresonance and the rotational antiresonance due to the offset of springs from the pivot axes of the DAVI inertia bar and to the distance between the pivots. However, by designing the DAVI such that the elastic axis is on the isolated pivot axis, then a = b and Equation (17) becomes

$$\omega^2_{A_R} = \frac{\omega^2_{A_T}}{(1 + \frac{r}{b})} \tag{18}$$

It is seen from this equation that the rotational antiresonant frequency for this DAVI design is always less than the translational antiresonant frequency. However, r/b is very small such that the discrepancies in antiresonant frequency are small.

CONCLUSIONS

This full-scale experimental study has demonstrated that rotor isolation is feasible using the passive DAVI isolation system.

1. Rotor isolation with the Kaman DAVI is feasible.

2. Vibration levels at the n-per-rev excitation frequency can be reduced to one-fifth to one-tenth the present values encountered.

3. Rotor isolation is feasible with 0.10-inch or less static deflection in the helicopter isolation system.

4. Rotor isolation can be achieved with a very stiff system without adversely affecting one-per-rev characteristics.

5. Reduction of vibration can be achieved throughout the complete fuselage structure.

6. A rotor isolation system can be designed for 2 percent or less of the gross weight and with normal structural stiffness design.

7. The natural frequencies of the system can be designed to be above one-per-rev, and therefore the possibility of mechanical instability occurring in flight is eliminated.

8. The vibratory relative deflection within the isolation system is small and within the conventional coupling and shaft design limitations now in use.

9. Rotor isolation will not necessarily increase the vibratory levels on the upper body or rotor.

RECOMMENDATIONS

This contractor recommends continued effort utilizing the results of this study toward the ultimate goal of operational isolation systems for helicopters.

Towards this goal, it is recommended that the analytical and test results obtained on the DAVI be substantiated with a flight test program. This flight test program should be conducted on a readily available helicopter that has an existing isolation system. This, then, would require minimum design and modification to incorporate the DAVI.

LITERATURE CITED

1. Daughaday, H., SUPPRESSION OF TRANSMITTED HARMONIC ROTOR LOADS BY BLADE PITCH CONTROL, Cornell Aeronautical Laboratories, Inc.; USAAVLABS Technical Report 67-14, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, November 1967.

2. Balcerak, J.C., and Erickson, Jr., J.C., SUPPRESSION OF TRANSMITTED HARMONIC VERTICAL AND INPLANE ROTOR LOADS BY BLADE PITCH CONTROL, Cornell Aeronautical Laboratories, Inc.; USAAVLABS Technical Report 69-39, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia.

3. Theobald, C.E.,Jr., and Jones, R., ISOLATION OF HELICOPTER ROTOR VIBRATORY FORCES FROM THE FUSELAGE, Kaman Aircraft Corporation; Wright Air Development Center Technical Report 57-404, September 1957.

4. Crede, C.E., and Cavanaugh, R.D., Barry Controls, Inc., and Abramson, H.N., Southwest Research Institute, FEASIBILITY STUDY OF AN ACTIVE VIBRATION ISOLATOR FOR A HELICOPTER ROTOR; Wright Air Development Center Technical Report 58-163, 1958.

5. Smollen, L.E., Marshall, P., and Gabel, R., A SERVO CONTROLLED ROTOR VIBRATION ISOLATION SYSTEM FOR THE REDUCTION OF HELICOPTER VIBRATION; Institute of the Aerospace Sciences, Paper Number 62-34, January 1962.

6. Schuett, E.P., PASSIVE HELICOPTER ISOLATION USING THE KAMAN DYNAMIC ANTIRESONANT VIBRATION ISOLATOR (DAVI), Kaman Aerospace Corporation; USAAVLABS Technical Report 68-46, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, December 1968.

7. Calcaterra, P.C., and Schubert, D.W., ISOLATION OF HELICOPTER ROTOR-INDUCED VIBRATIONS USING ACTIVE ELEMENTS, Barry Research and Development; USAAVLABS Technical 69-8, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, June 1969.

8. Anderson, R.C., and Smith, M.F., A STUDY OF THE KAMAN DYNAMIC ANTIRESONANT VIBRATION ISOLATOR (DAVI), Kaman Aerospace Corporation; USAAVLABS Technical Report 65-75, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, January 1966.

9. Jones, R., AN ANALYTICAL AND MODEL TEST RESEARCH STUDY ON THE KAMAN DYNAMIC ANTIRESONANT VIBRATION ISOLATOR (DAVI), Kaman Aerospace Corporation; USAAVLABS Technical Report 68-42, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, November 1968.

10. Jones, R., FLIGHT TEST RESULTS OF A DAVI ISOLATED PLATFORM, Kaman Aerospace Corporation; USAAVLABS Technical Report 70-57, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, November 1970.